Conditioning a Cryogenic Sapphire Oscillator with GPS Reference

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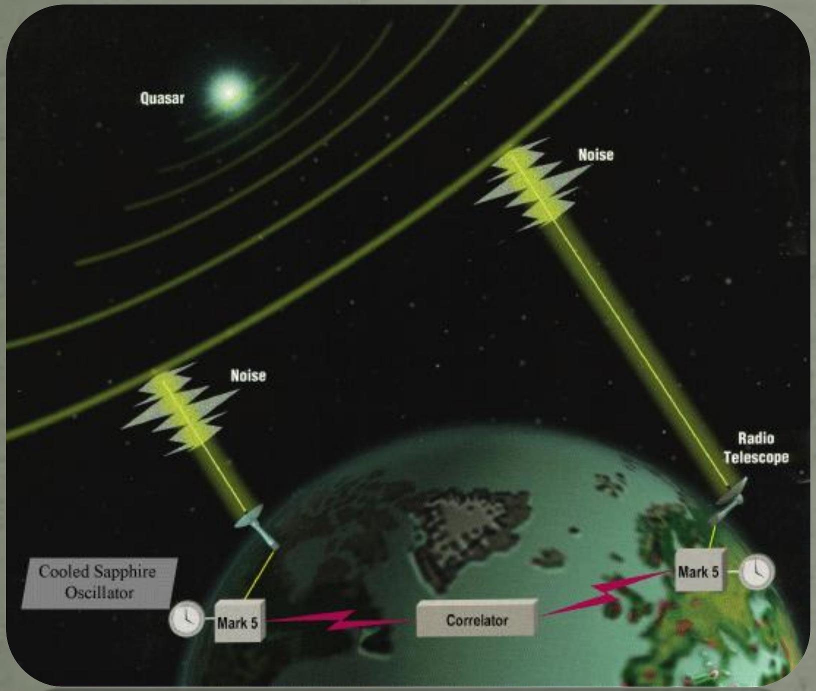
Introduction – alternative frequency standard for VLBI



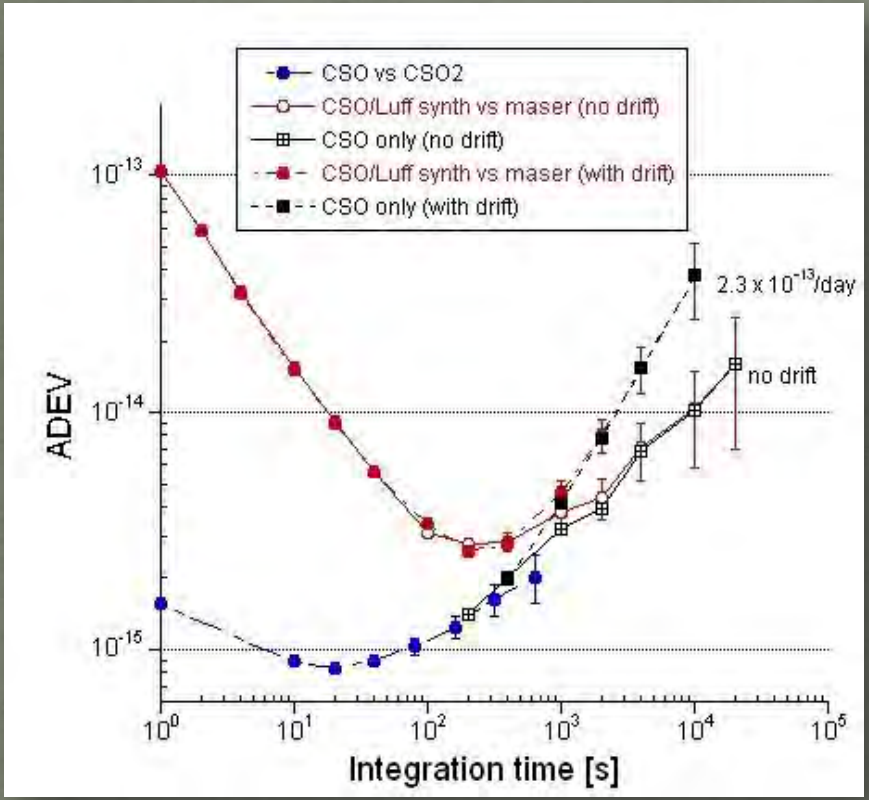
- For the high resolution and large separation between telescopes, VLBI requires high quality frequency standards.
- Hydrogen masers is the most commonly used reference.
- Cryogenic Sapphire Oscillators could provide better reference for high frequency VLBI.

Presentation Outline

Westford CSO (nicknamed Penny) developed by John Hartnett

- CSO vs. H-maser
- CSO receiver
- GPS feedback control loop
- Factors contributing to instability
- Analyzing the system with simulation
- Future improvements

CSO vs. H-maser



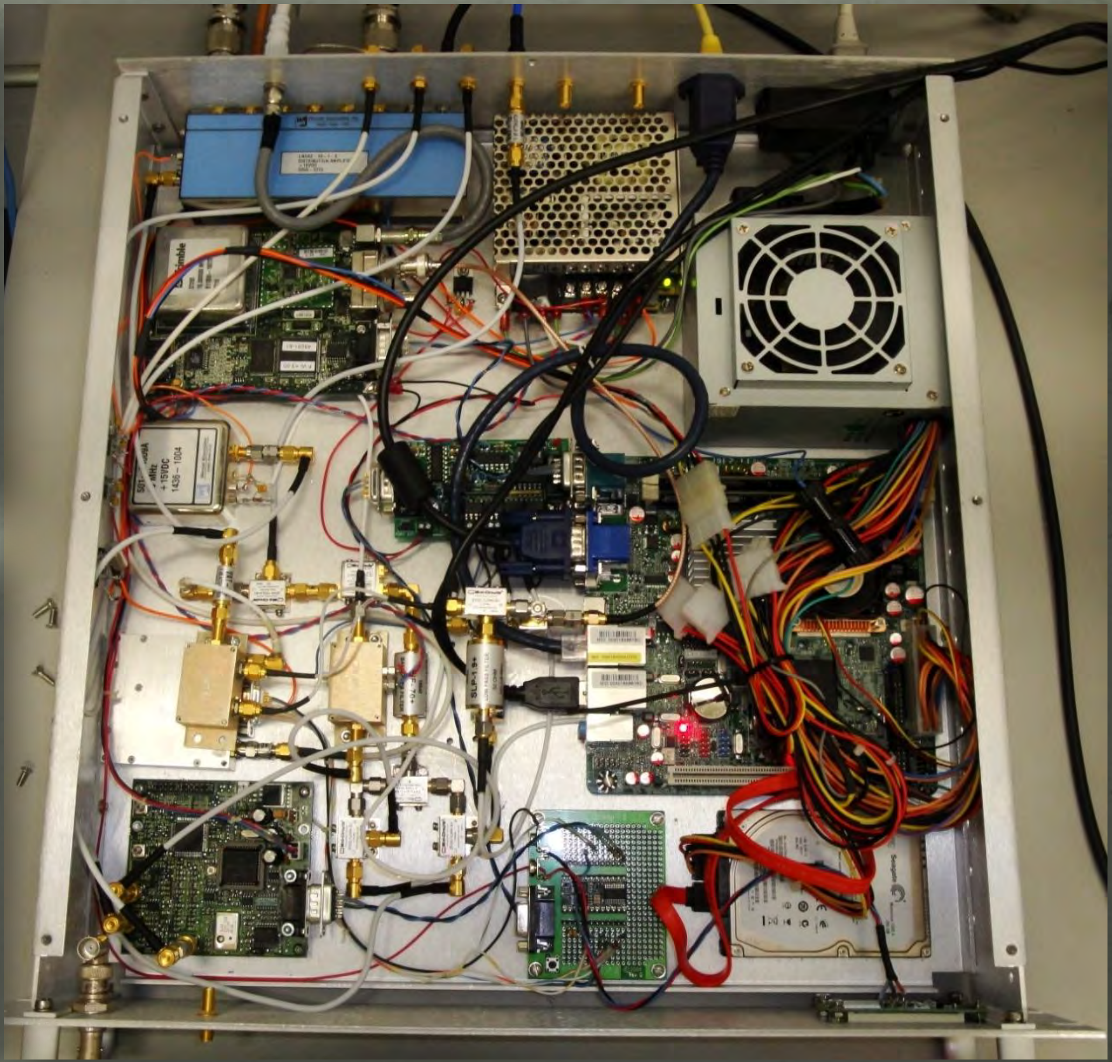
Allan Deviation – statistical measure of the fractional frequency stability

- CSOs have much better stability than H-masers on time scales shorter than 100s.
- But CSOs are prone to frequency drifting and random walk of frequency on longer time scale.
- To improve long term stability of CSO, a GPS feedback control loop is implemented.

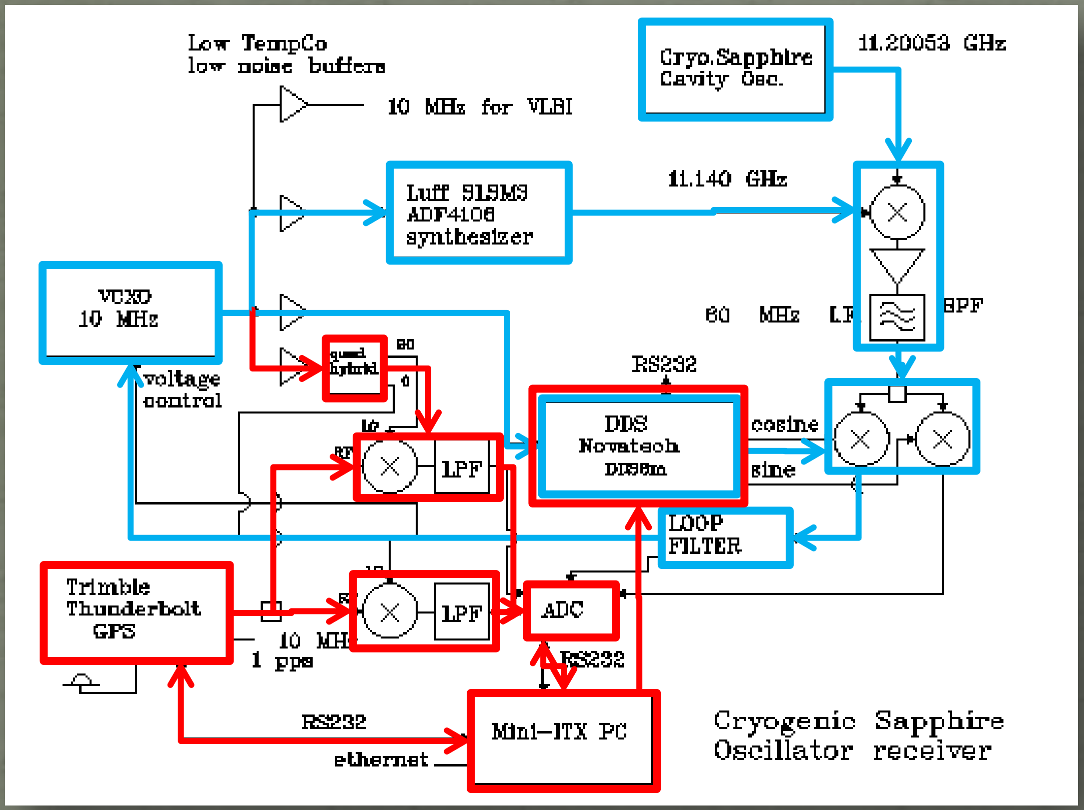
The CSO Receiver

CSO receiver designed and built by Alan Rogers

TSC 5115A phase noise test set



The CSO Receiver

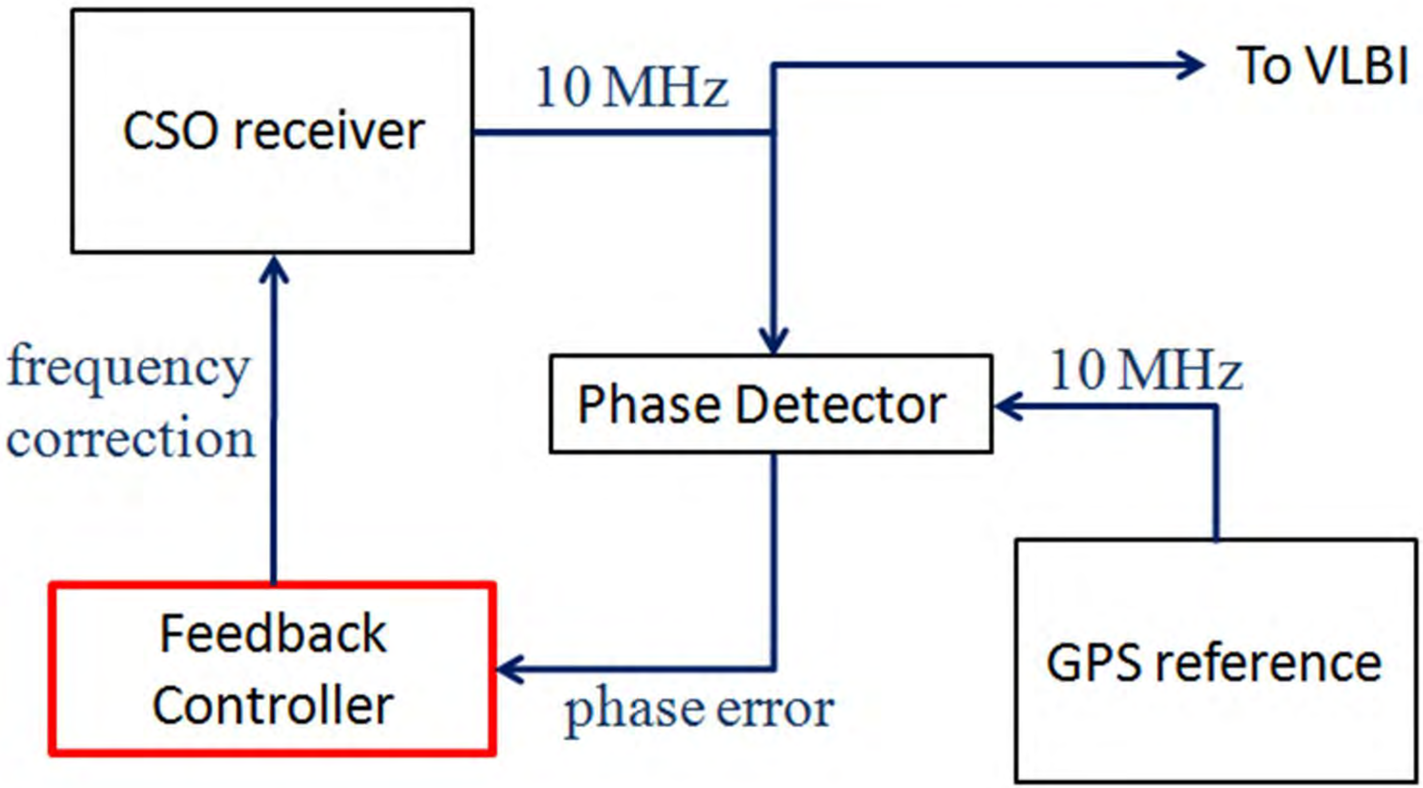


Hardware PLL

Software GPS feedback control loop

- The receiver derives a 10 MHz signal from the 11.2 GHz output of the CSO
- Hardware loop locks a 10 MHz high-quality crystal oscillator to CSO.
- Software loop disciplines the 10MHz output with GPS reference

Simplified Block Diagram of GPS Feedback Control Loop

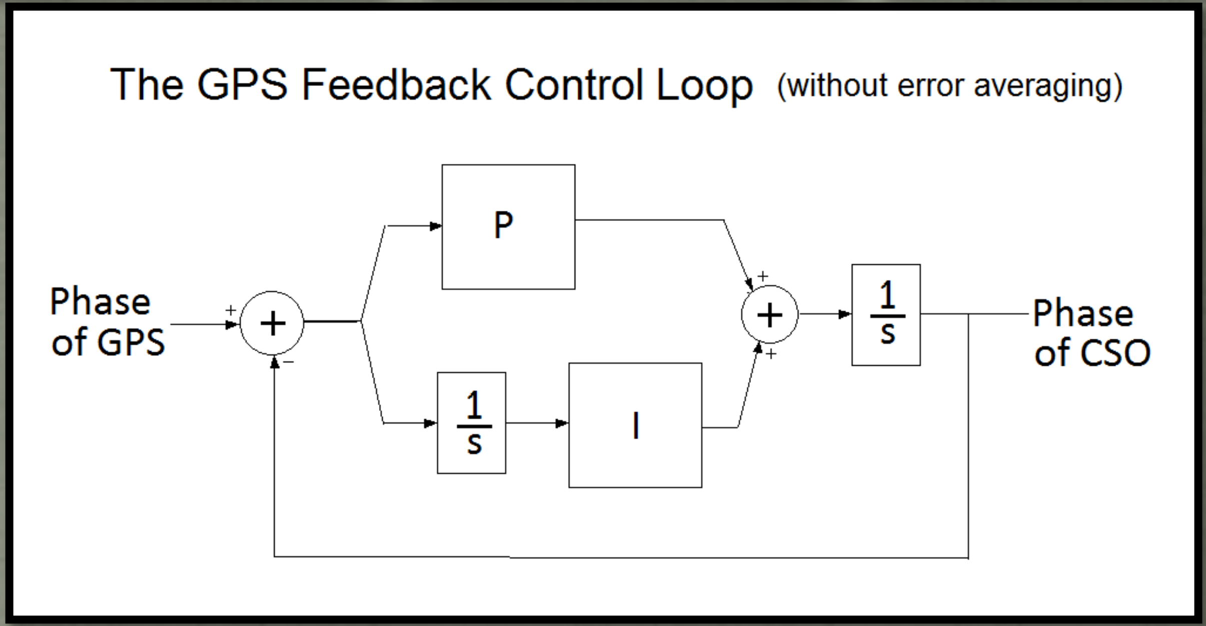


GPS Feedback Control Loop

$$\mathrm{Corr}(t) = Pe(t) + I\int_0^t e(t')dt'$$

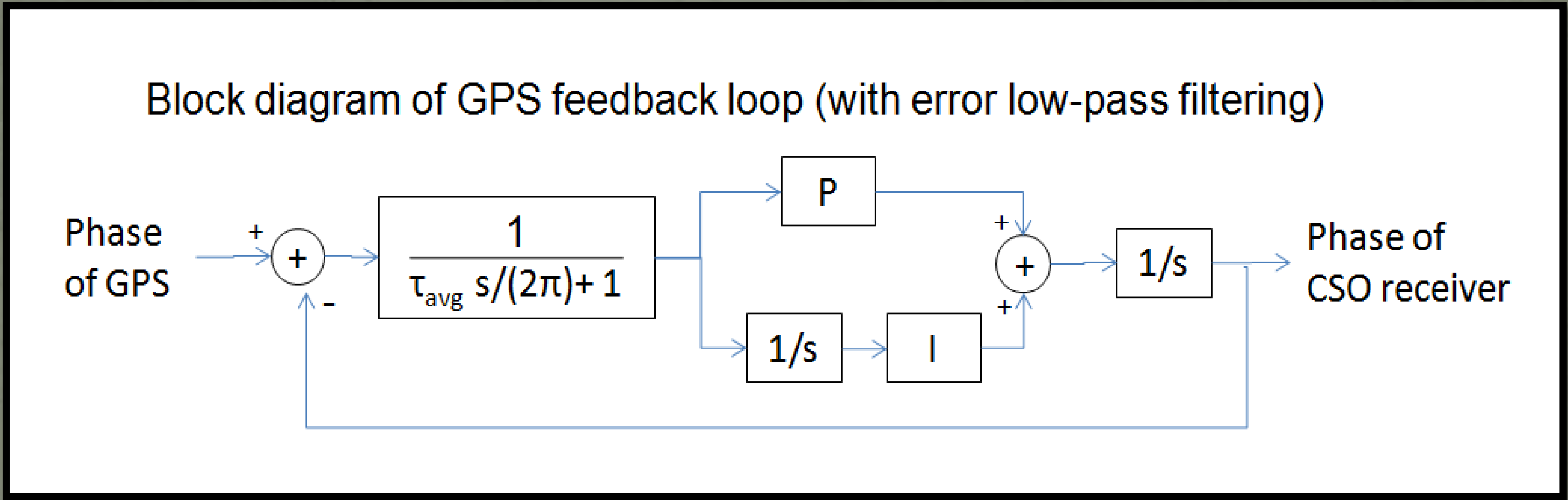
$$\frac{\phi_{cso}}{\phi_{gps}} = \frac{Ps + I}{s^2 + Ps + I}$$

$$P = \frac{4\pi\zeta}{\tau} \quad \text{and} \quad I = \frac{4\pi^2}{\tau^2}$$



- Feedback loop is implemented in software as a proportional-integral controller
- User specifies the time constant (τ) and damping factor (ζ) of the feedback loop.

GPS Feedback Control Loop

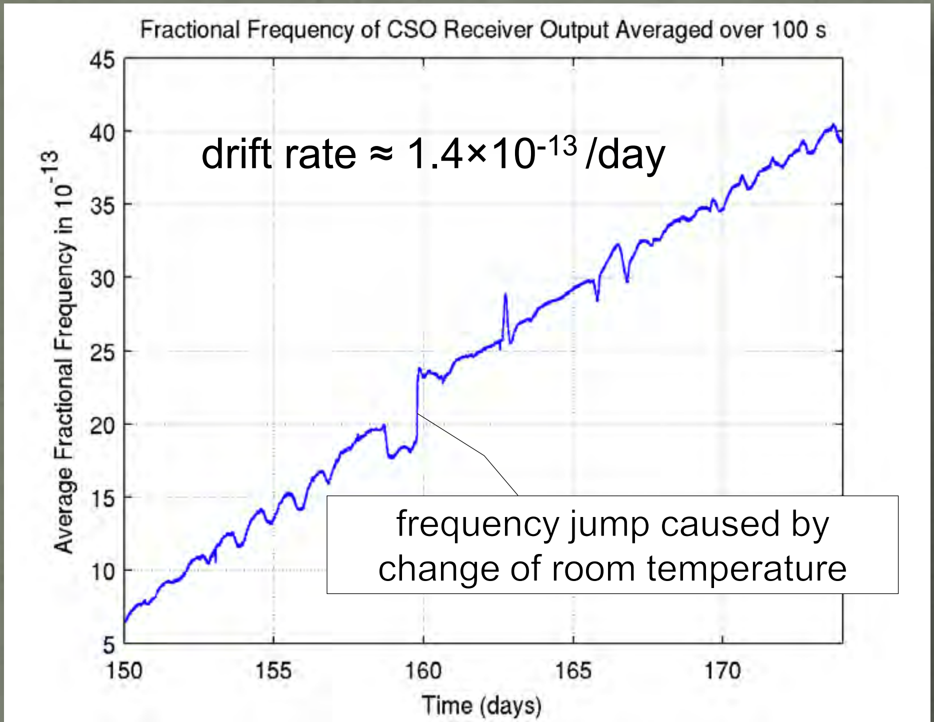


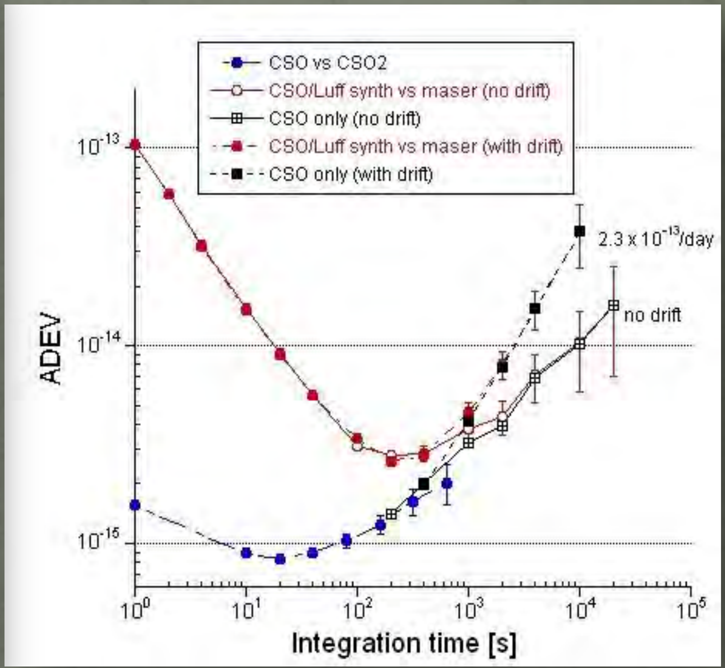
- To prevent noise of the GPS receiver output from degrading the CSO, the phase error is averaged over time in the feedback loop.
- Error averaging introduces delay into the feedback loop, which can cause instability.

Factors contributing to Instability

- Frequency drift due to aging of CSO
  1.4×10^{-13} /day
- Temperature sensitivity of the CSO controller
  2.1×10^{-13} /°C, time constant ~1.5 hr
- Noise and Diurnal variation of the GPS signal

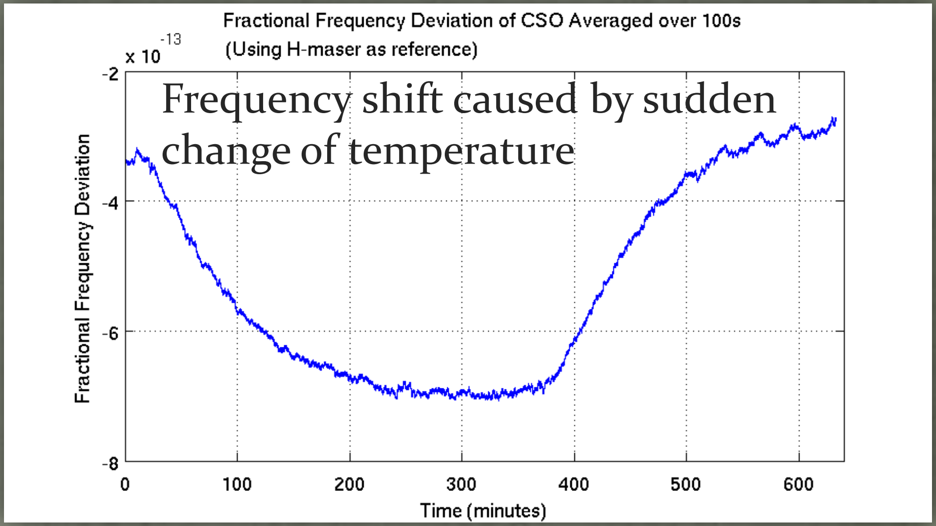
CSO Noise and Frequency Drift





- The output of the CSO on time scale longer than 1000 s is dominated by random walk frequency noise and flicker frequency noise.
- Due to aging, the CSO frequency drifts at a rate of about 1.4×10^{-13} per day.
- The frequency drift due to aging is corrected by feedforward control.

Sensitivity to Temperature

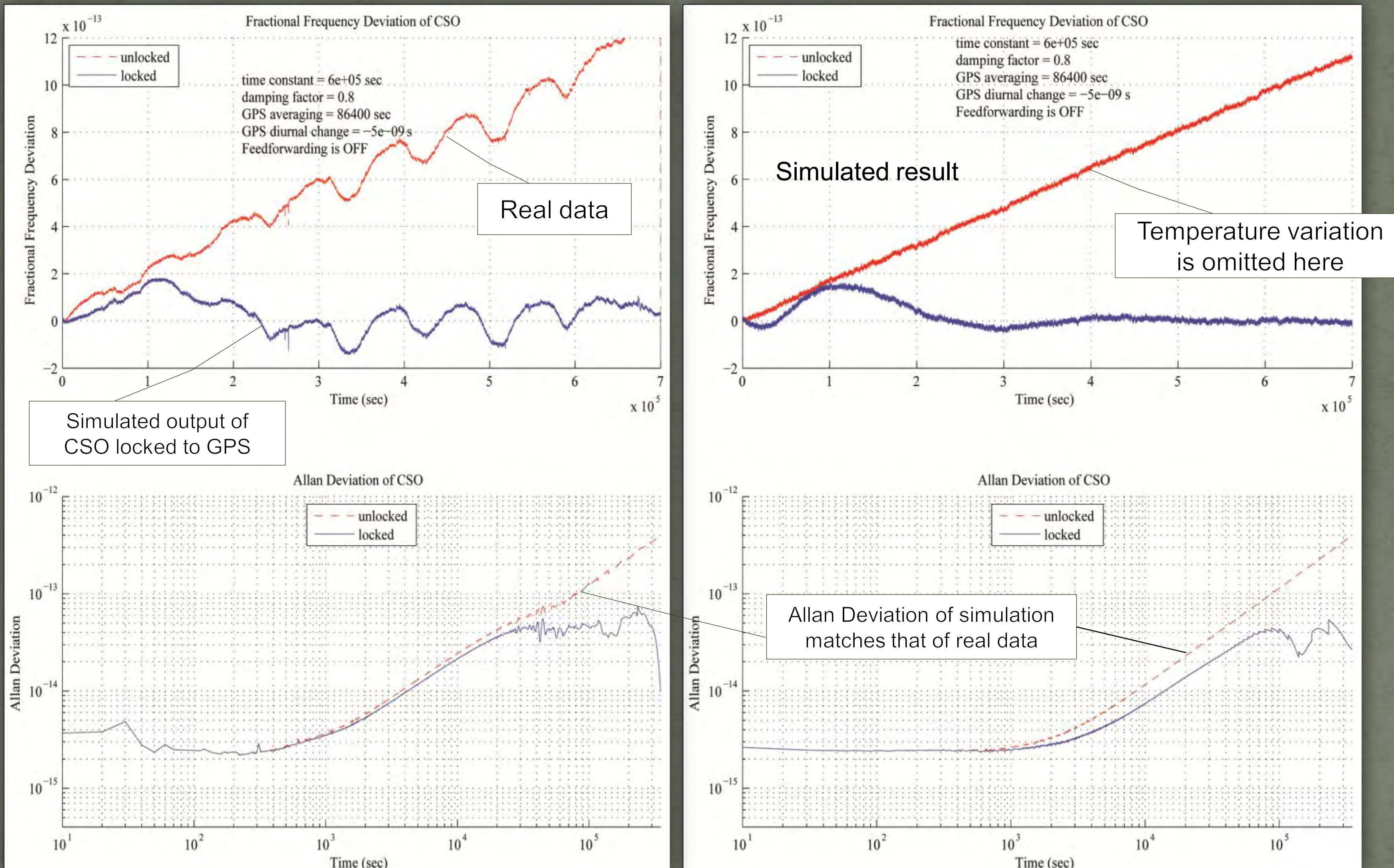


- The oscillation of the CSO is controlled by electronics in a box on top of the dewar. The frequency of the controller is sensitive to ambient temperature change.
- The controller has a temperature coefficient of about -2.1×10^{-13} /°C and a time constant of about 1.5 hours.
- Frequency shift caused by temperature change is modeled and compensated for in software.

Optimizing Loop Parameters

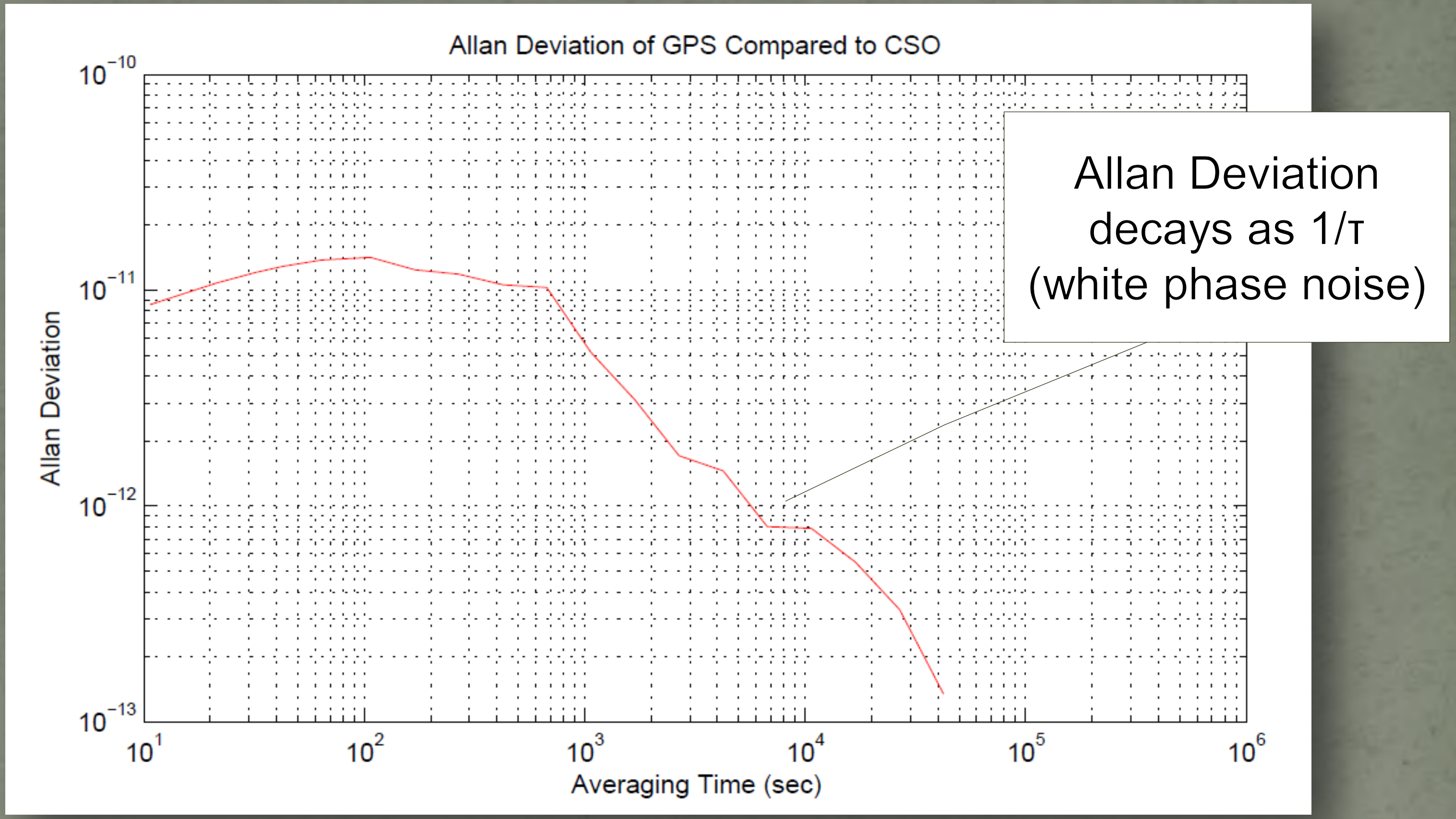
- The loop parameters include:
  1. Error averaging time (τ_{avg})
  2. Loop time constant (τ)
  3. Damping coefficient (ζ)
- Experiments on the real system is too time-consuming.
- To solve the program efficiently, software simulation tools were developed to analyze the performance of the feedback loop with parameters of different values.

Modeling the CSO Receiver Output



- CSO receiver output is modeled with flicker frequency noise and a constant frequency drift.

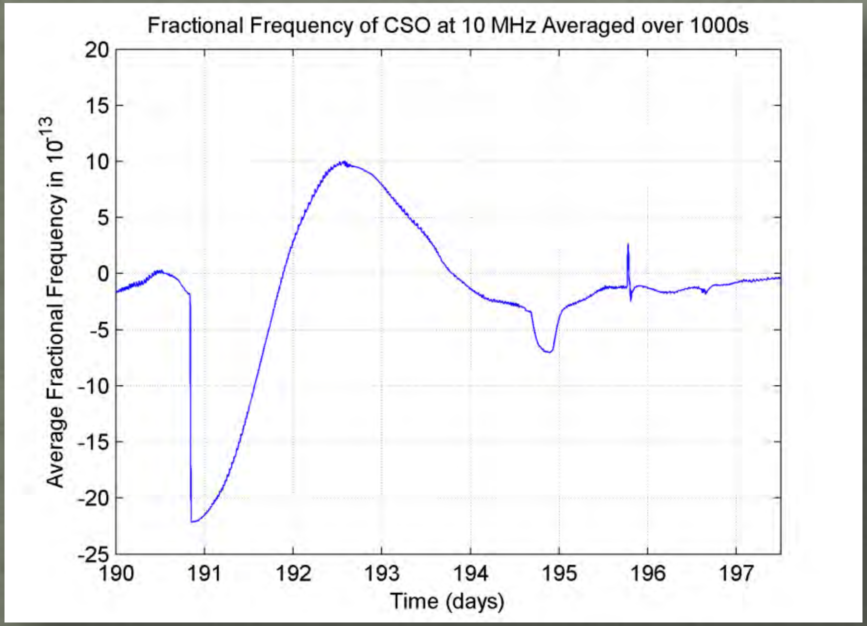
Modeling the GPS Reference



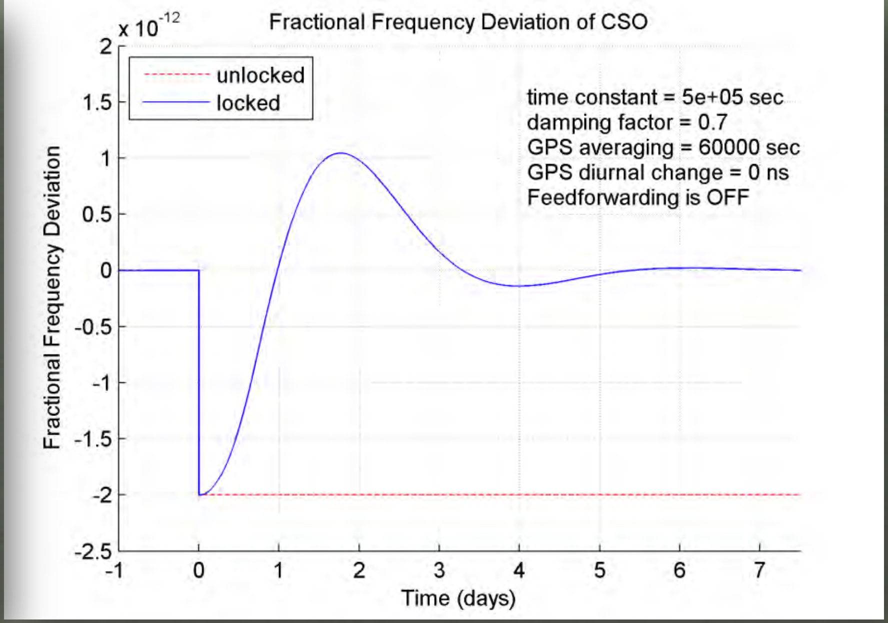
- GPS signal is modeled with white phase noise of about 3.8 ns and a diurnal phase fluctuation.

Comparison – Step Response of Real and Simulated System

Response of real system

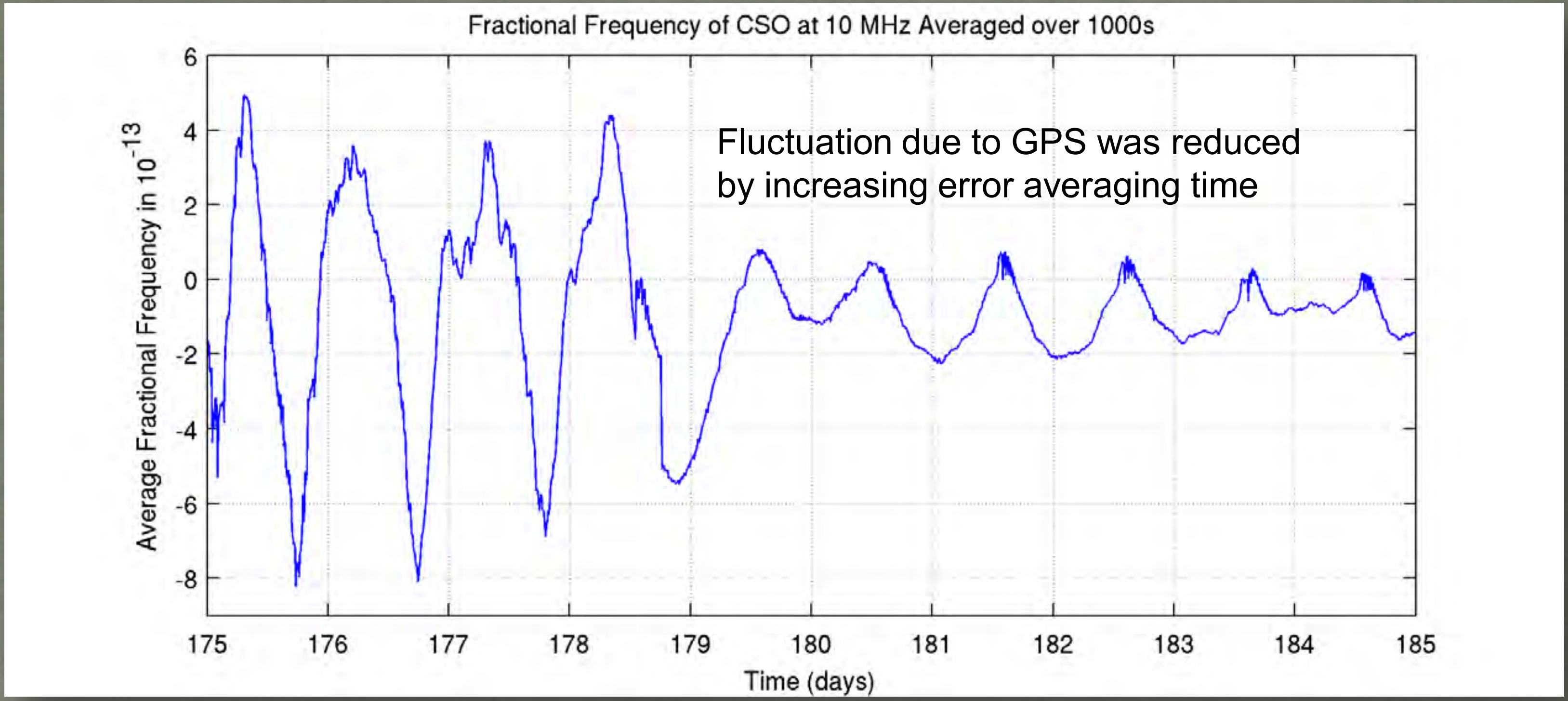


Simulated step response



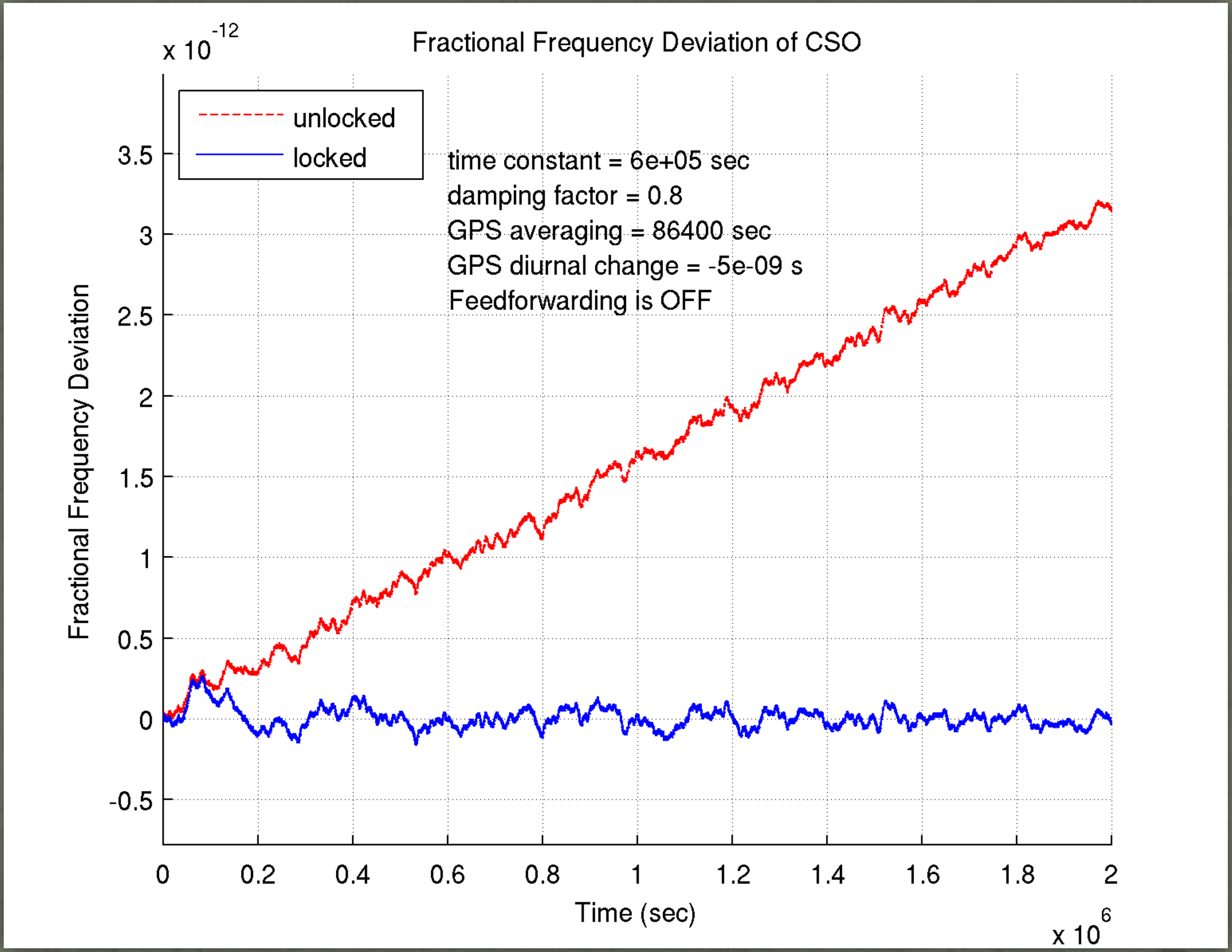
The simulation correctly models the step response of the real system.

Observed GPS Diurnal Variation

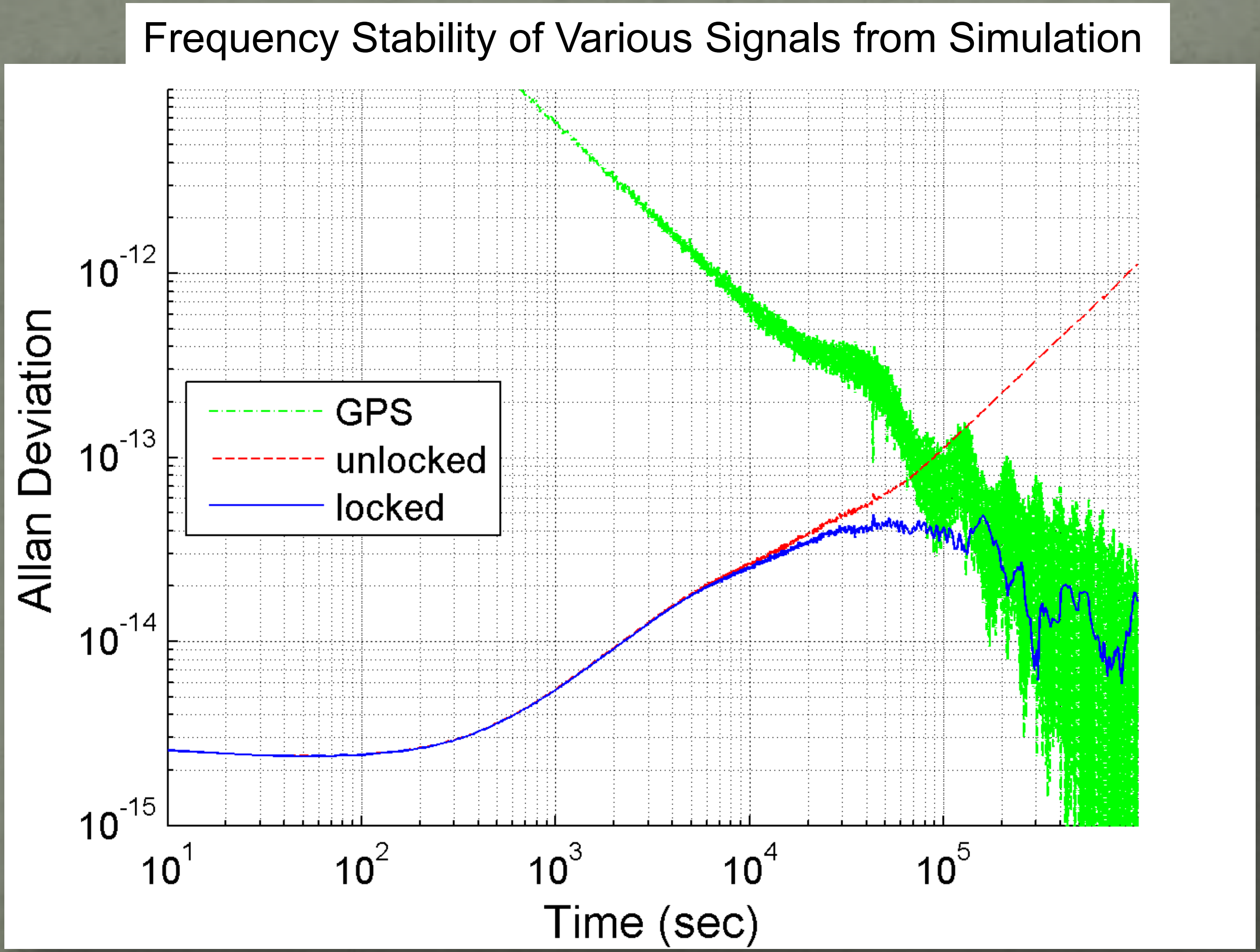


- Without the diurnal variation, a error averaging time of 10^4 s and a time constant above 10^5 s is sufficient.
- The error averaging time needs to be set to a day long to eliminate the significant diurnal fluctuations in the GPS signal.

Simulation using Optimized Parameters



Simulation using Optimized Parameters



Future Work and Improvements

- Analyze the performance of temperature compensation.
- Collect more data to evaluate long term stability of CSO receiver.
- Acquire temperature of the CSO controller directly by using a thermometer in the box.
- Transfer CSO to a constant temperature environment.
- Use a dual-channel (L1 & L2) GPS receiver that automatically corrects for ionospheric delay.

Summary

- CSO is potentially a better frequency standard for high frequency VLBI.
- A controller system is developed to increase the long term stability of the CSO.
- Stability of the system is mainly limited by diurnal variations of the GPS reference signal and frequency fluctuations due to temperature change.
- A simulation program was used to predict system performance and optimize loop parameters.
- Improvements can be made in the future by temperature regulation and by using a better GPS reference.

Acknowledgements

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