Robust Control of Frequency Standards in the Presence of Systematic Disturbances

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***Abstract*— Frequency steer limits are important aspects that influence the overall response and design of a robust control system. We study the effects that frequency steer limits have on the response of a control system when underlying components of the system have undergone non-stochastic perturbations. Examples of the disturbances include environmental changes and hardware anomalies. Additionally, we attempt to find a balance between the performance of the control system and the robustness of maintaining parameter limits in the presence of outlying events. Performance of design strategies are evaluated utilizing both simulated and archived measured data.**

I. Introduction

The U.S. Naval Observatory (USNO) maintains several steered clock systems. Each system is comprised of a hydrogen maser that provides a frequency signal to a high precision frequency synthesizer. This synthesizer is steered toward its target based on a time error. The principal differences between any two of these systems are the measurement systems that provide the phase value, the algorithms used, and the target of the control. The motive for this study is to determine how limiting parameters for a steering algorithm may affect the responsiveness of the control due to perturbations that were not included in the system design models. The objective is to determine if the control limits calculated using simulation previously [4] for a noisier system are performing adequately for the operational USNO Master Clock (MC) in both steady-state and during non-stochastic disturbances. We will look at the responses of the filtered control systems with respect to certain offsets.

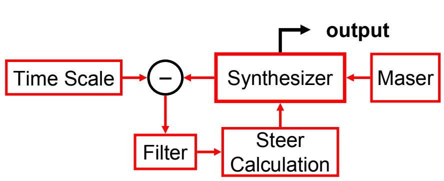

Figure 1. Block diagram of a typical control system that creates a physical realization of a timescale.

II. History of Steering USNO Master Clock

A. Previous Design

Prior to November 2004 the USNO MC was steered in frequency once per day using a control that attempted to take out the entire frequency error and a fraction of the phase error relative to the USNO A.1 mean which is itself steered to UTC. The state estimate, phase and frequency offsets with respect to the steering goal, were determined by fitting a line to the available data since the last steer. The magnitude of an individual steer was not allowed to exceed 1.75e-15 which is equivalent to a change in phase of 150 picoseconds over one day. While this design was sufficient for nominal operations, an event, such as a temporary outage in temperature control of a chamber, could perturb the system for up to 23 hours before steering would take out any resulting clock error. Depending on the size of the event, the limitations placed on the individual steer might not allow steering to fully correct the error. This was a contributing factor in the decision to change to more frequent steers.

B. Present Design

Since November 2004 the USNO MC has been steered in frequency once per hour using a control that has a time constant of 4 days. The present design utilizes a Kalman filter [1,3] that provides a better state estimate for the MC relative to a real-time hydrogen maser mean than the previous design. This improves the short term stability utilized as the input to the control system. The magnitude of an individual steer may not exceed 2.7e-16, and the accumulated effect of the hourly steering may not move the MC more than 200 picoseconds over any 24 hour period. Figure 2 gives examples of minimal clock changes that would require the use of the present steering limits and the control response to these events.

Even though this design has the potential to be more aggressive than the previous design, it has proved to be much gentler. In fact, as figure 3 shows, the range of the accumulated effect of steering over a day under the present design is approximately a third of the range of accumulated effect under the previous design. This is partially explained by the ability of the present design to react more quickly to an event which allows for the correction to be much smaller.

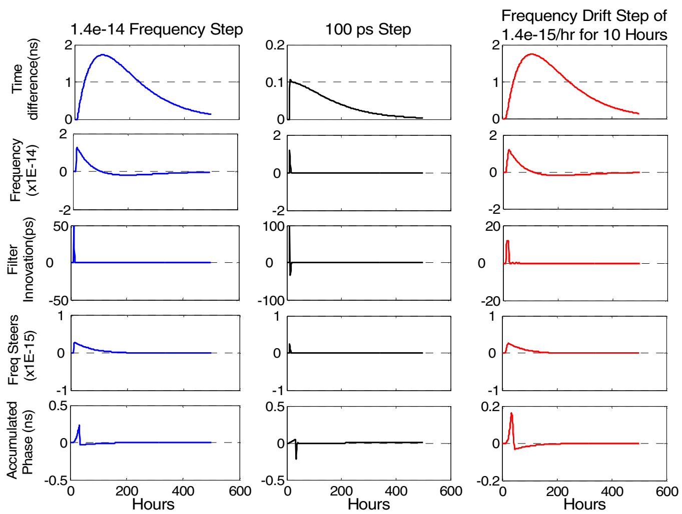

Figure 2. Shows the minimum frequency, phase, and drift steps that will cause the 2.7e-16 steer limit to be reached in the present system design.

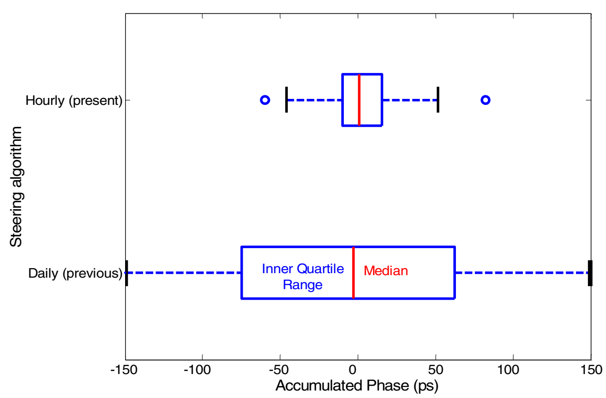

Figure 3. Box plot of daily accumulated phase of the previous and present control system designs.

III. PROPOSED DESIGN CHANGES

The present design has proven to be more than sufficient for normal conditions. In many respects it far exceeds the necessary conditions for nominal operations as is easily evidenced by how far within the limits the control has remained over the several months analyzed which is shown by figure 4. While having a system that can react to events without raising alarms is not necessarily a bad thing, it would be more advantageous for the control limits to be kept in line with what is required in day-to-day operations while having the flexibility to expand those limits in the presence of an event that calls for more aggressive steering. This requires a more reasonable set of limitations, a means of detecting a problem, and the determination of an expanded set of limitations sufficient to deal with any problem we can foresee.

A. *More Restrictive Limits*

As figures 3 & 4 plainly show, control of the MC can be maintained in normal conditions by limits for an hourly steer of 1.0e-16 and an accumulated phase effect of 100 picoseconds over any 24 hour period. Over the several months analyzed, only 7 times have we required a single steer in excess of this new hourly limitation and only three times have we required an accumulated effect in excess of the new 24-hour limitation. Figure 5 provides examples of events sufficiently large to require a maximum steer and the control reaction to those events. The events are all well within the expected performance parameters of a hydrogen maser under normal conditions.

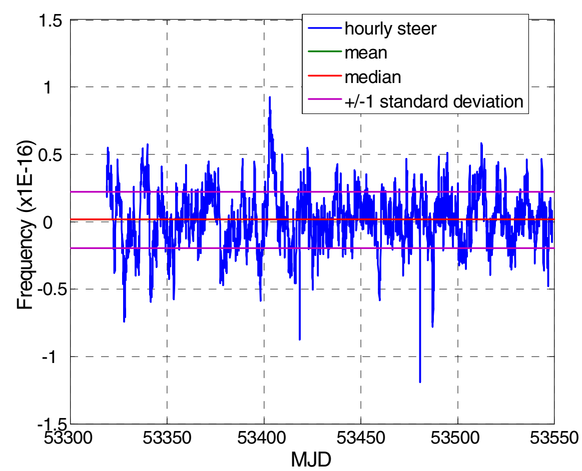

Figure 4. Frequency steers of the operational USNO Master Clock.

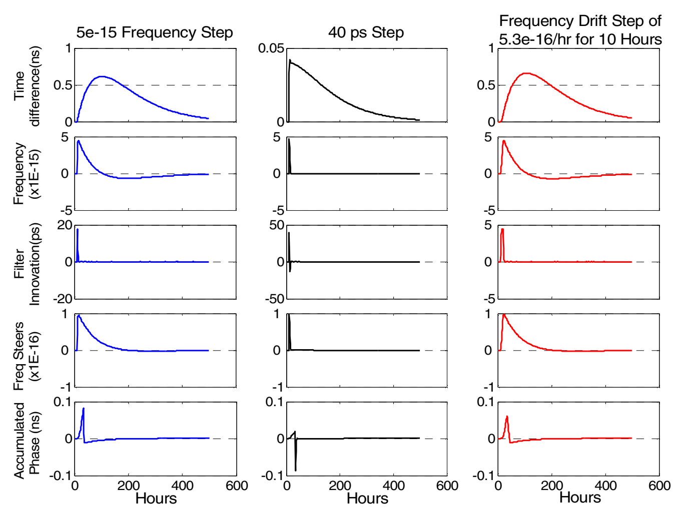

Figure 5. Shows the minimum frequency, phase, and drift steps that will cause the 1e-16 steer limit to be reached in the proposed system redesign.

B. Detecting and Reacting to Anomolies

Under the more restrictive limits, early detection of potential perturbations to the MC becomes critical to operations. Finding a large step in phase is relatively easy due to frequent comparisons between the MC and independent back up master clocks also located at USNO. The cause of the step can also be found without much difficulty due to the measurement of the MC components against both the MC and the back ups. In most cases, these hardware failures will require manual intervention to repair or replace a component, and the step generally must be removed in hardware as well.

Detection of a step in frequency is slightly more difficult since frequency must be estimated from phase measurements. However, proactive steps can be taken to predict such frequency changes by watching for events that are known to cause a change in maser frequency: e.g. change in environmental conditions, change in maser parameters. These are monitored frequently, and a simple Shewart chart [2] allows for the detection of a significant change in conditions that might lead to a MC frequency change that would require more aggressive steering. A distribution determined from analysis of historical data is assigned to each data set that is monitored, and behavior of that data set that is not consistent with the assigned distribution will raise an alarm. The more restrictive steering limits may be employed until such an event occurs. At that point, limits may be expanded to a level that will allow automatic steering to maintain control. It is assumed that if the frequency offset is calculated to be larger than the expanded limits can handle that the event is catastrophic and human involvement is necessary for that system.

Following the detection of an anomaly that can not be attributed to the system reference or target, new expanded limits must be set for the control. The present limits of 2.7e-16 and 200 picoseconds over any 24 hour period are sufficiently aggressive for most events that would not require human intervention for repair.

C. Analysis

The MC data from November 2004 to June 2005 was de-steered and used as the input for a simulation that steered the clock using the proposed design. During this period of time there were no events that required an increase of steering limits, so the steers applied were limited to the proposed 1.0e-16 for each hourly steer and no more than 100 picoseconds of accumulated phase over any 24 hour period for the entire data set. MC deviation from the steering goal was not increased using these new limits, and stability of the MC was similarly unaffected.

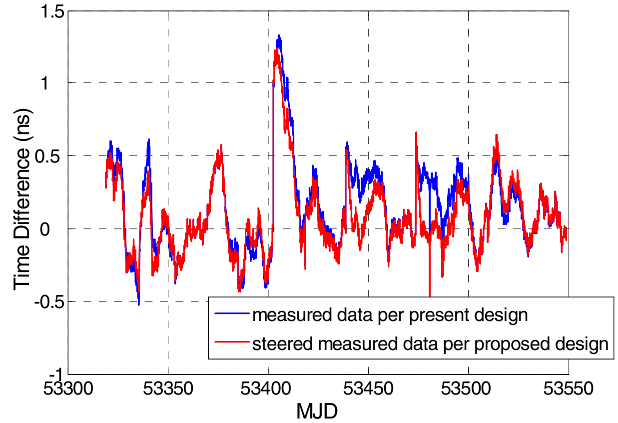

Figure 6. Time Difference of the Master Clock vs. USNO timescale as measured during operations and re-steered in simulation with the proposed 1E-16 steering limit.

IV. Conclusion

We have determined that the control limits proposed in [4] are too broad for our Master Clock system design. This is likely due to the conservative estimates used for simulating the performance of the underlying hydrogen maser and the better short term stability of the Kalman filter estimates utilized for the present Master Clock system input. We now propose a more robust solution with tighter steering limits and intelligent decision making that will adjust the limits if any divergence is found to be the result of a perturbation to the steered components of system and not the reference timescale.

References

[1] R. G. Brown and P. Y. C. Hwang, 1992, Introduction to Random Signals and Applied Kalman Filtering, 2nd ed., John Wiley & Sons, New York.

[2] D. C. Montgomery, 1997, Introduction to Statistical Quality Control, 3rd ed., John Wiley & Sons, New York

[3] K. Ogata, 1995, Discrete-Time Control Systems, 2nd ed., Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

[4] J. Skinner and P. Koppang, "Effects of parameter estimation and control limits on steered frequency standards," 33rd Annual Precise Time and Time Interval (P'ITI) Meeting, pp. 399-406, 2001.