Simulation of a High Stability Reference Clock for Small Satellites with Modeled GPS Timing Errors

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Introduction

• SmallSats are increasing in popularity, but for small satellites to serve in some additional important roles, they must meet more challenging system timing requirements

• Chip Scale Atomic Clocks (CSACs) provide very good stability for timeframes of a few hours, but are not as good for shorter or longer timeframes

• By combining CSACs with other timing sources such as GPS and crystal oscillators, we can improve both short term and long-term stability

• Understanding the nature of GPS errors for the orbit of interest is critical to accurately assess the stability of the combined system
Low SWAP, High Stability Clock System Design

- Previous research investigated methods for creating a high stability reference clock for small satellites by combining a heterogeneous group of oscillators:
  - Multiple CSACs, a GPS receiver and an Evacuated Miniature Crystal Oscillator (EMXO)
- The performance was compared for LEO missions with and without a GPS reference, and demonstrated that RMS time errors of ~500 ps would be possible with GPS timing errors modeled as additive white Gaussian noise
High Stability Clock System Performance

- Resulted in excellent simulated performance, providing a 6x improvement over the CSAC$_{avg}$, with time error standard deviation $\sim$0.5 ns
- Combined ADEV at $10^4$ seconds has dropped from a little over $10^{-12}$ down to $10^{-13}$, a tenfold improvement over the GPS AWGN model
- Typical behavior for clock ensembles would limit the stability to the performance of the most stable ensemble member (CSAC$_{avg}$)
- However, the simulation showed a dramatic improvement for timeframes above 1000 seconds
- White noise model is likely optimistic in some ways
- Simulation with higher fidelity GPS time errors is needed!
Realistic GPS Timing Error Simulations

• LEO orbit position calculated for several days for a circular orbit
• GPS pseudorange errors are modeled:
  • Receiver Noise
    • Simulated receiver noise was modeled as AWGN with a standard deviation of 5 cm for single frequency scenarios, and 7.5 cm for dual frequency scenarios
    • Noise levels assume carrier smoothing has been used to reduce the pseudorange noise
  • Control Segment Errors (SISRE)
    • Broadcast ephemerides compared to post-processed precise Antenna Phase Center (APC) position and clock errors from the NGA
  • Ionospheric delay
• Point solution time errors calculated by comparing estimates generated from pseudoranges with errors to true LEO position and time
**SISRE**

- GPS receiver time errors caused by SISRE for a 450km LEO orbit show a standard deviation of 1.8 ns
  - Maximum offset is over 9ns for this two-day period
- Errors are characterized by sharp jumps, connected by sloped segments, because the LEO spacecraft is constantly acquiring and dropping GPS satellites
Ionosphere

- Total Electron Content (TEC) maps were downloaded from the International GNSS Service (IGS) to use as the baseline (truth)
- Time interpolation was performed to estimate the TEC at times between the map epochs
- Used a Chapman profile to estimate the fraction of the ionosphere remaining above the LEO satellite altitude
- Calculated the effective height as the 50% height above the LEO
- Applied an obliquity factor to account for the longer path from GPS satellites with lower elevation
- Calculated the group delay of pseudorange measurements
# Ionospheric Simulation Scenarios

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<th>LEO Altitude</th>
<th>GPS Days</th>
<th>Dual Frequency (Iono Free)</th>
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<th>Iono Model</th>
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Ionospheric Errors
• Dual frequency, iono-free approach is best for missions with lower LEO orbits and tight timing requirements
• Benefit of using ionospheric models is evident for single frequency
• 10 ns AWGN bounds ADEV for nominal 450 km orbit without compensation
EMXO-CSAC-GPS CLOCK SIMULATION

- 450 km iono-free GPS receiver time errors were used in the high-performance time system simulation

- The system clock shows stability improvement of nearly 30% vs. GPS, CSACavg, and the EMXO for timeframes below 1000 seconds

- Comparing the performance of the EMXO-CSAC-GPS clock system with 450 km LEO SISRE errors against the system with the AWGN GPS model shows increased time errors due to the more accurate GPS model

- The non-AWGN character of the simulated GPS with SISRE errors prevents the Kalman filter from improving the overall stability for time frames above 1000 seconds.
Conclusions

• This work provides a more realistic assessment of the combined clock system performance

• Simulation of the time estimates for a LEO GPS receiver revealed two important conclusions:
  • Using a 10 ns white noise model for the GPS time error alone is overly conservative for iono-free GPS point solutions
  • However, white noise does not adequately reflect the error characteristics of the GPS point solution time estimate

• Use of the simulated LEO GPS receiver time error in the high-performance clock simulation shows that the system time error was overly optimistic when using AWGN GPS time error
  • Although the simulated LEO GPS receiver time errors were lower than the AWGN model used previously, the combined EMXO-CSAC-GPS system performance was worse, increasing from 0.5 ns to 1.3 ns

• The combined system represents a viable high-performance timing system for small satellites in LEO!
Thank You!
References

- Microsemi, "Quantum SA.45s CSAC, Chip Scale Atomic Clock Datasheet," Microsemi.