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Comparative Performance Analysis of Time Transfer Architectures for LEO-PNT Systems

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Extended Abstract

This paper compares two distinct architectures for timekeeping in Low Earth Orbit Position, Navigation, and Timing (LEO-PNT) satellite constellations: (1) the use of less accurate on-board clocks with frequent time transfer from GNSS in Medium Earth Orbit (MEO) or satellites in Geostationary Earth Orbit (GEO) such as Satellite Based Augmentation System (SBAS), and (2) clock updates using inter-satellite communication links within the LEO constellation.

In the first approach, less accurate and cost-effective on-board clocks, such as Chip-Scale Atomic Clocks (CSACs), are used instead of more precise options like Oven-Controlled Crystal Oscillators (OCXOs). The reason for choosing CSACs over OCXOs is mainly due to their smaller size, lower weight, and reduced power consumption, making them ideal for space applications with stringent size, weight, and power (SWaP) constraints. While OCXOs offer better accuracy, they are bulkier and more power-hungry, which increases the overall cost and complexity of the system. With CSACs, precise time can still be maintained through frequent synchronization with GNSS or GEO satellites, which offer external time reference, though this approach does introduce dependency on external systems and potential vulnerabilities in case of GNSS or SBAS signal degradation or unavailability.

The second approach proposes the use of highly stable clocks in a subset of LEO satellites, referred to as master clocks, while the rest of the constellation uses less accurate clocks. Instead of traditional atomic clocks, miniature rubidium clocks like the Safran mRO-50 (or other miniature rubidium clocks) can serve as master clocks due to their high stability, low size, and power efficiency. These clocks require infrequent updates from ground stations because of their minimal frequency drift. The less accurate clocks in the constellation are then synchronized through inter-satellite communication links, which may use radio frequency (RF) or optical time and frequency transfer. While optical links offer higher precision, they introduce additional hardware complexity and power consumption. This architecture enhances system autonomy, reducing reliance on external systems like GNSS, but it does increase the complexity of inter-satellite communication design and power requirements.

Overall, the first approach is optimal for cost-sensitive applications with minimal SWaP requirements, while the second approach offers higher autonomy and reliability at the cost of increased complexity. The choice of architecture depends on mission needs, operational constraints, and the desired balance between cost, independence, and precision.