Enhanced Performance and Security in GNSS Master Clocks

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Enhanced Performance

- **Multi-system GNSS capability**
- **Standard OCXO holdover oscillator**
  - **Premium higher-performance OCXO or rubidium**
- **Oscillator trajectory prediction**
- **Real-time, continuous estimation of actual holdover errors (patent pending)**
- **High-reliability HO architecture (patent pending)**

Multi-system GNSS

- **Compatible with all current and future GNSS systems:**
  - **GPS, current and new Block III (31, operational)**
  - **GLONASS (Russia) (24, operational)**
  - **Galileo (EU) (4, in orbit validation)**
  - **BeiDou/Compass (China) (0, B1-C interoperable)**
  - **SBAS systems (WAAS, EGNOS etc.)**
- **Provides redundancy - other systems may still be usable if GPS is jammed or spoofed**

OCXO holdover oscillators

- Standard performance level: < 1 ms / 24 hours
  - Typical performance < 5×10^{-9} (5 ns/s)
  - Excellent short-term stability, allows us to be conservative if we detect receiver problems, suspected spoofing, bad time points
- Premium performance level: < 10 us / 24 hours
  - Usable holdover performance for high stability requirements such as synchrophasors

Rubidium holdover oscillator

- **Rubidium oscillator performance: < 5 x 10^{-11} / month**
- **1 us / day performance class**
  - **Usable accuracy for synchrophasors for up to a month of holdover, likely more**

Holdover oscillator trajectory prediction

- Measure actual HO performance in real time
- Extremely accurate, digital-domain measurements of HO frequency (patent pending)
- Models known systematic effects on HO frequency (rate), mostly temperature and time (aging)
- Provides enhanced holdover performance, compared to baseline oscillator specifications (typically 5 - 10 times improvement)

Real-time estimation of HO prediction uncertainty (patent pending)

- **Continuously estimates the uncertainty in the HO prediction algorithm (mostly due to HO noise)**
- **Asks the question "What would be the HO error right now, if we had lost lock (30 minutes, 24 hours, etc.) ago? (For *this clock*, not generic)**
- **Asks this question for a sequence of these pro-forma holdover intervals, going back in time**
- **Performs a statistical analysis, and**
- **Determines a tolerance interval for a user-specified confidence level: 2 sigma, 3 sigma, etc.**

Real-time holdover uncertainty estimation

Holdover interval	Estimated uncertainty
15 min.	21 ns
30 min.	31 ns
60 min.	42 ns
2 hours	93 ns
4 hours	0.22 us
8 hours	0.53 us
12 hours	0.82 us
24 hours	1.78 us
2 days	4.0 us
4 days	7.9 us
7 days	18.4 us
14 days	43 us
30 days	107 us

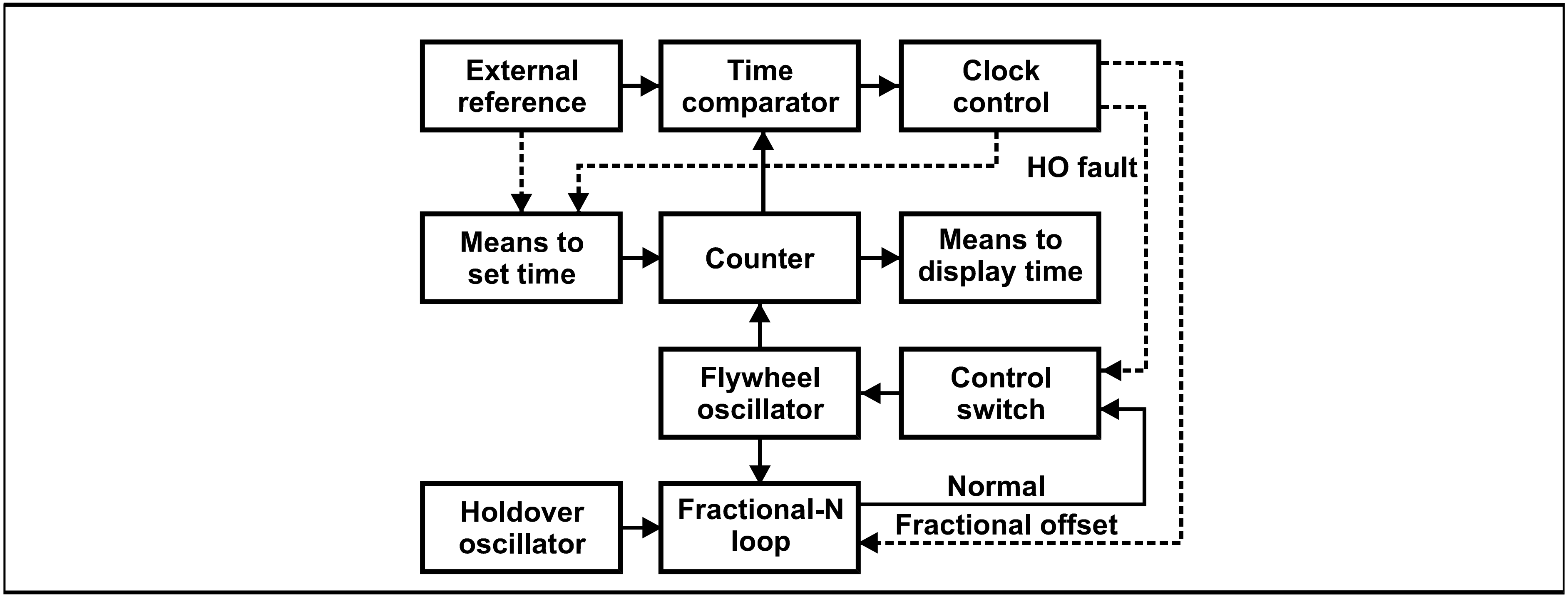
High-reliability HO architecture (patent pending)

- **Removes HO as critical path of failure**
- **Fails over to VCXO (providing similar performance to existing clocks)**
- **Why? HO failure rate is higher than basic clock**
- **Mostly due to high temperature (ovenized) operation of electronics**
- **Arrhenius equation: failure rate approximately doubles for each 10 degrees C increase, per component (= 2^6 or 64x at 85 C, relative to 25 C)**

High-reliability HO architecture

- **Delivers excellent time accuracy if either GNSS or HO is unusable**
- **Time error degrades only if both GNSS is unusable and the HO has failed**
- **This is an extremely unlikely combination of circumstances**
- **Providing enhanced, N+1 operational reliability**

High-reliability HO architecture



Enhanced Security

- Secured communications interfaces
- Anti-spoofing - two levels
- Clock errors bounded by HO performance (i.e., can't be worse than the HO)
- Learn, Normal, Unlocked and Alarm (spoofing) operational states
  - Normal mode highly conservative vs. promiscuous
- Redundant power supply and GNSS receiver can provide additional security

Secured communications interfaces

- **Serial communications**
  - **Limit plain text ASCII commands (non-critical)**
  - **Most commands use proprietary binary protocol**
  - **Secure encrypted commands require authentication**
- **Ethernet communications**
  - **Configurable HTTP or HTTPS web interface**
  - **Limited SSH console interface**
  - **Both web and console interfaces require authentication**

Basic anti-spoofing

- **Learn ‘typical’ operational characteristics in the first ~24 hours operation, e.g.:**
  - **Signal strengths**
  - **Antenna location**
  - **Satellite visibility (restricted sky view, if any)**
- **Then, monitor for changes which might indicate spoofing (or satellite or receiver problems)**
- **If spoofing or degraded performance is suspected, use holdover until problem can be evaluated**

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Advanced, cryptographically-secure anti-spoofing (patent pending)

- Spoofers typically transmit from a single location; satellites are distributed across the sky
- This causes a detectable difference in received signal carrier phase if the antenna is moving
- We use synthesized motion (no actual moving parts) of the antenna electrical center
- Using a cryptographically-secure, pseudo-random pattern of motion, to defeat remote sensing (and prediction) of the antenna motion
- Preventing spoofer from overcoming the method

Errors always bounded by HO performance

- **Once in normal, 'conservative' state, clock will reject any attempt to change timing by more than the HO error bounds**
- **Allowing normal tracking of GNSS signals**
- **But rejecting spoofing, external time changes, satellite and receiver errors, etc.**
- **Based on fact that time is highly redundant: once you know the time, you know the time forever**
- **Within the accuracy of your oscillator**

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Timebase processor states

- Learn: ~ 24 hours, clock determines its operational environment and parameters
- Normal: highly conservative, for enhanced security against external events of whatever type
- Unlocked: GNSS signals are unavailable (broken antenna, failure, jamming, etc.)
- Alarm: Spoofing or system failure suspected, causing unexpected change in time, position, satellite visibility, signal strength etc.

Highly-conservative normal operation

- Time is highly redundant
- Only two (three) things needed to make a clock:
  - An initial time fix (means to set the clock)
  - An accurate rate (means to advance the time)
  - Means to display or output time in a useful way
- Given: We have a good holdover oscillator
- Then: We can ignore anything that tells us that time is changing in any unexpected way
- Else: If all is well, we can track the GNSS

Summary

- Enhanced Performance
  - Multi-system GNSS for redundancy, better accuracy
  - Holdover oscillators with enhanced reliability, trajectory prediction and uncertainty estimation
  - Multiple levels of HO performance
- Enhanced Security
  - Secured communications
  - Two levels of anti-spoofing
  - Errors bounded by HO performance
  - Highly-conservative normal operation state

Thank you!