Operational Composite Clock for Satellite based Augmentation Systems (SBAS)

Matthias Suess, Marion Goedel, Johann Furthner and Michael Meurer
Synchronization of Clocks within SBAS System

Local area station network, e.g. EGNOS or WAAS

GNSS satellite segment, e.g. GPS or Galileo

Timing function of SBAS

- Provision of GNSS satellite clock parameters
- Provision of UTC parameters
- How is system time generated?
Evolution: Satellite Composite Clock

Now: Composite clock with ground atomic clocks

- Driving cost factor
- Maintenance effort of atomic clocks

Evolution: Cost reduction and increase of robustness

- Composite clock with satellite clocks
- Minimum number of atomic clocks at ground
- Simplification of maintenance
Agenda

1. Key Challenges and Operational Solutions
2. Experimentation Results with Synthetic Clock Offsets
3. Experimentation Results with IGS Network Data
No Permanent Monitoring of Satellite Clocks

- Rising and falling of satellite clocks
- No permanent measurements of satellite clock

- Uncontrolled entry can affect composite clock
- Controlled mechanism required
Kalman Filter to Predict Satellite Clock Offsets

- Stochastic Model of Satellite Clock Offset

\[
\begin{align*}
\begin{pmatrix}
x_n(t_k + \tau) \\
y_n(t_k + \tau) \\
d_n(t_k + \tau)
\end{pmatrix}
& =
\begin{pmatrix}
1 & \tau & \frac{1}{2} \tau^2 \\
0 & 1 & \tau \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
x_n(t_k) \\
y_n(t_k) \\
d_n(t_k)
\end{pmatrix}
+ \\
\begin{pmatrix}
w_{x,n}(\tau) \\
w_{y,n}(\tau) \\
w_{d,n}(\tau)
\end{pmatrix}
\end{align*}
\]

- Non observed satellite clocks are predicted by their model

\[\hat{x}(t_k) = \hat{x}^-(t_k) + k(C_{GB}^{-1}(t_{k-1}))(Z(t_k) - H_x(t_k)\hat{x}^-(t_k))\]

- Operational covariance controls weight contribution to the composite clock
Worse Stability of Receiver Clock

- Ground receivers required to track satellite clocks
- Worse stability of internal receiver clocks
- How to mitigate contribution in composite clock?
Differencing to Exclude Receiver Clocks

- Contribution of receiver clock drops
- Increase of measurement noise modelled by Kalman filter
- Varying reference satellite modeled by Kalman filter
Experimentation Results with Synthetic Clock Offsets
Synthetic Scenario Definition

- Nominal 24 GPS satellite constellation
  - 17 RAFS
  - 7 Space Caesium (SC)

- Two observation noise scenarios
  - OBS 0: 1E-21 [s^2]
  - OBS 1: 1E-17 [s^2]

RAFS: Rubidium Atomic Frequency Standard
Satellite Composite Clock Estimates of RAFS

RAFSs Estimates with Observation Noise 0

RAFSs Estimates with Observation Noise 1

- Satellite Composite Clock more stable than any RAFS
Time Deviation Increases due to Non-observability

Increase of synchronization error due to non-observability

Corrected satellite clock represent composite clock
Stability of Satellite Composite Clock

- Satellite composite clock better than square-root of 10 RAFS
- Satellite clocks can be estimated against composite clock
Experimentation Results with IGS Network Data
Experimentations with IGS Rinex Data

- Robustness requirement against operational events
- Design of an operational satellite composite clock [1]
  - Initialization relative to GPS time
  - Detector and mitigation
- Generation of time transfer data
- Calibration of clock and observation noise

[1] Paper appendix with operational algorithms
Real-Data Verification of GPS Satellite Clocks

Satellites with Space Cesium

- Reaches assumed clock performance

Satellite with Space Cesium

- Limitations by time transfer results
- Dependency on clock models identified

Block IIR with RAFS

Better performance by RAFS
Estimation of Satellite Composite Clock to GPS Time

Satellite composite clock relative to GPS Time

Robust generation of composite clock

Stabilities of satellite composite clock to GPS Time

Daily stability of around 4E-14 [s/s]
Conclusion

- Successfully system time generated without atomic clocks on-ground
- Usage of satellite composite clock provides important features
  - Increase robustness
  - Reduce maintenance and hardware costs
- Important role of satellite prediction and clock models
- IGS real-data evaluation verifies concept
- Proposal for evolution of SBAS timing architecture
APPENDIX