Operational Composite Clock for Satellite based Augmentation Systems (SBAS)

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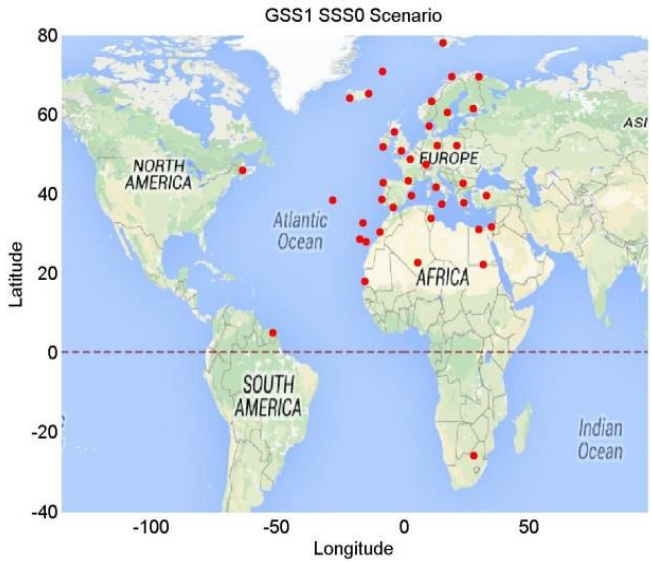
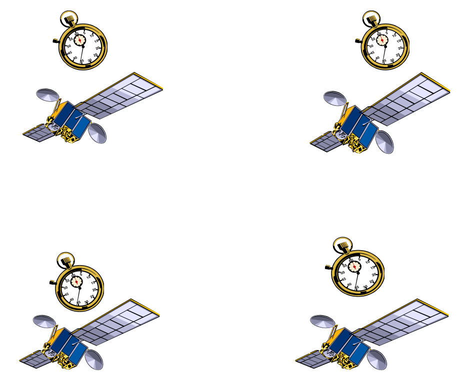
DLR

Synchronization of Clocks within SBAS System

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



GNSS satellite segment,
e.g. GPS or Galileo

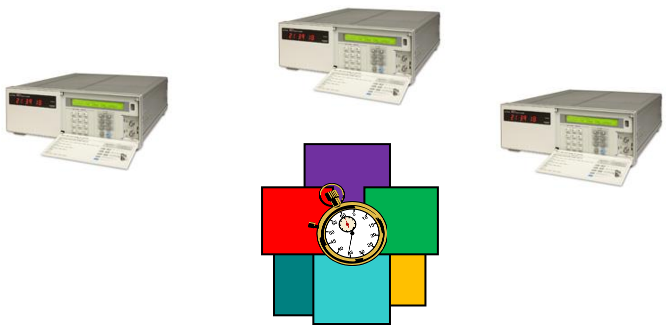


Timing function of SBAS

- Provision of GNSS satellite clock parameters
- Provision of UTC parameters
- How is system time generated?

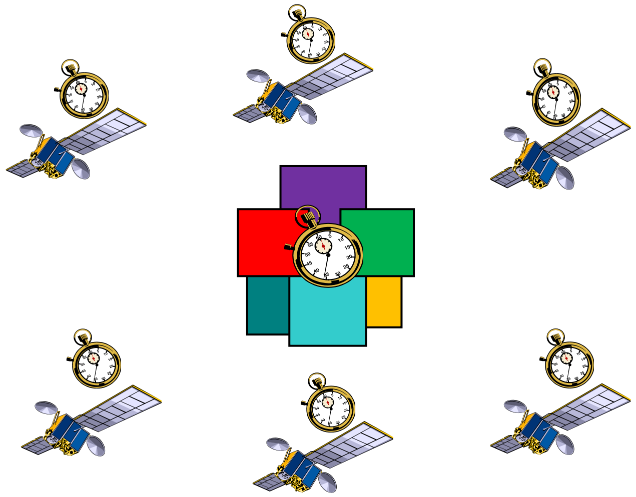
Evolution: Satellite Composite Clock

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

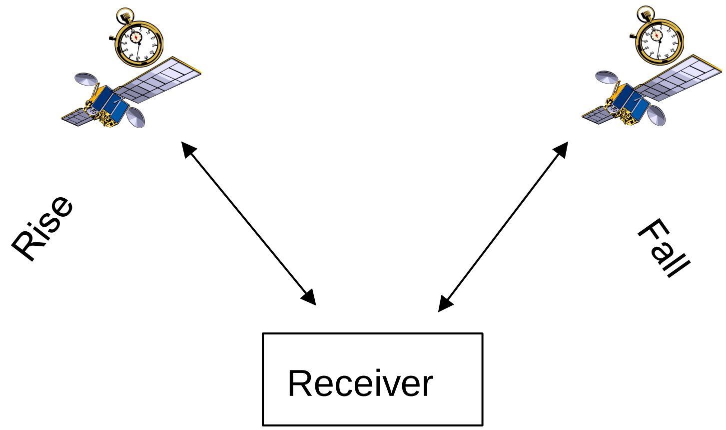
1. Key Challenges and Operational Solutions

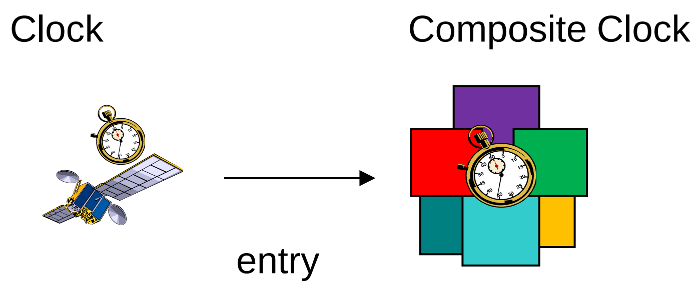
2. Experimentation Results with Synthetic Clock Offsets

3. Experimentation Results with IGS Network Data

IGS: International GNSS Service

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

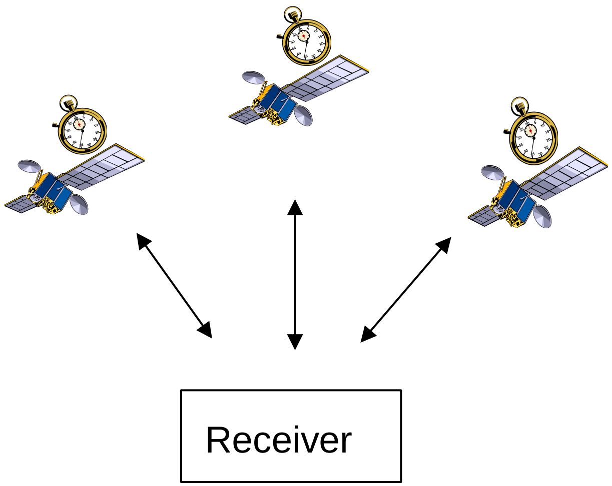
$$\begin{pmatrix} x_n(t_k+\tau) \\ y_n(t_k+\tau) \\ d_n(t_k+\tau) \end{pmatrix} = \begin{pmatrix} 1 & \tau & \frac{1}{2}\tau^2 \\ 0 & 1 & \tau \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_n(t_k) \\ y_n(t_k) \\ d_n(t_k) \end{pmatrix} + \begin{pmatrix} w_{\mathrm{x},n}(\tau) \\ w_{\mathrm{y},n}(\tau) \\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

- Non observed satellite clocks are predicted by their model

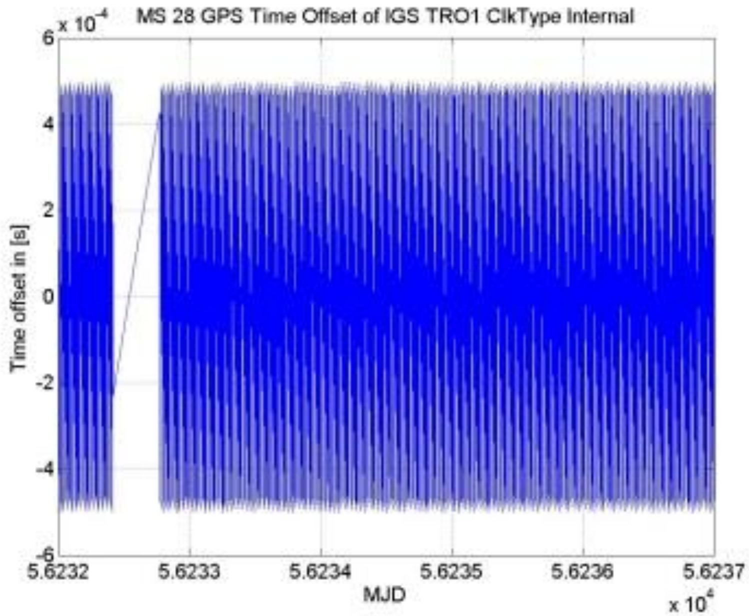
$$\hat{\mathbf{x}}(t_k) = \hat{\mathbf{x}}^-(t_k) + \mathrm{k}(\mathbf{C}_{\mathrm{GB}}{}^-(t_{k-1}))(\mathbf{Z}(t_k) - \mathbf{H}_{\mathrm{x}}(t_k)\hat{\mathbf{x}}^-(t_k))$$

- Operational covariance controls weight contribution to the composite clock

Worse Stability of Receiver Clock

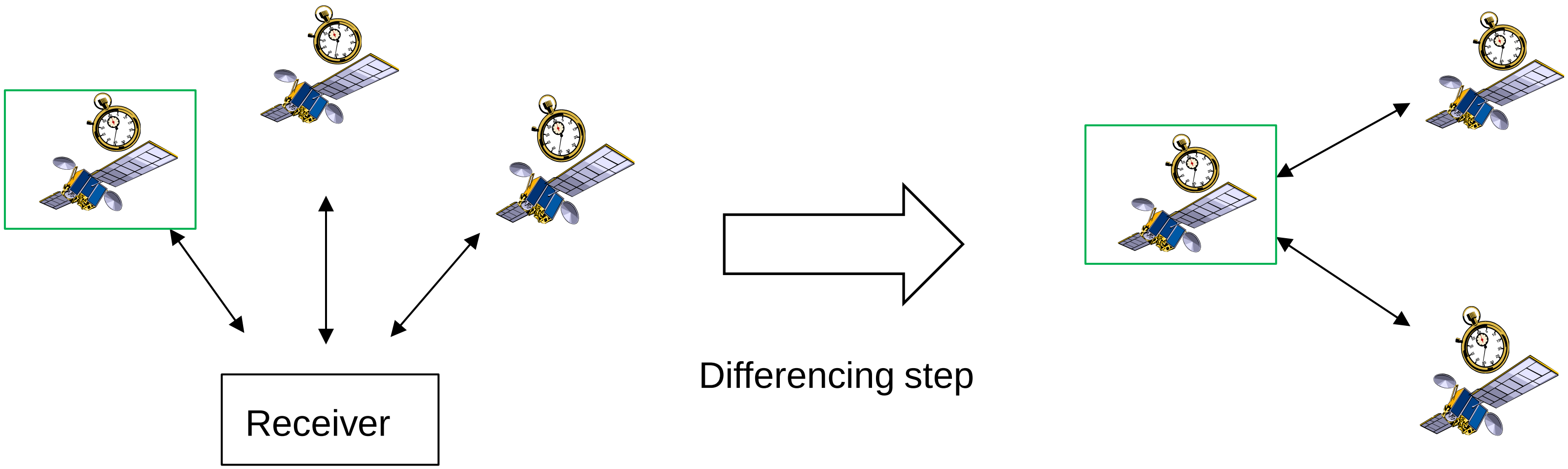


Receiver clock solution to GPS time



- 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



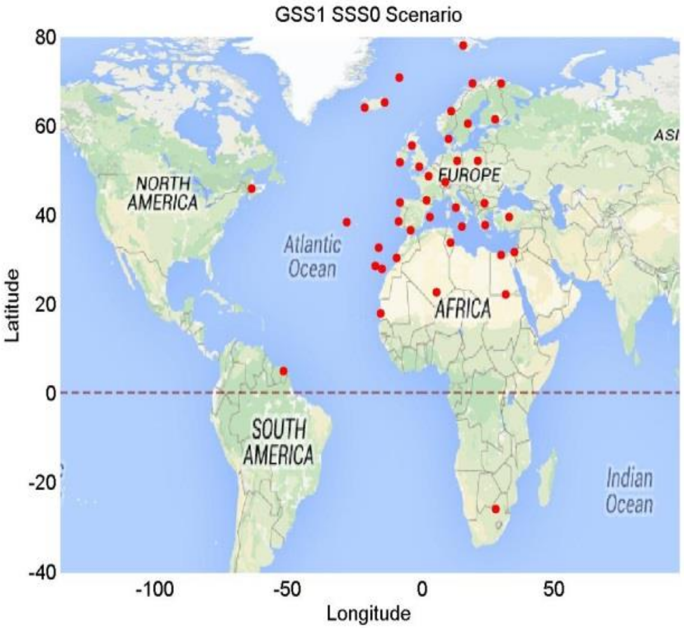
- Contribution of receiver clock drops
- Increase of measurement noise modelled by Kalman filter
- Varying reference satellite modeled by Kalman filter

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]

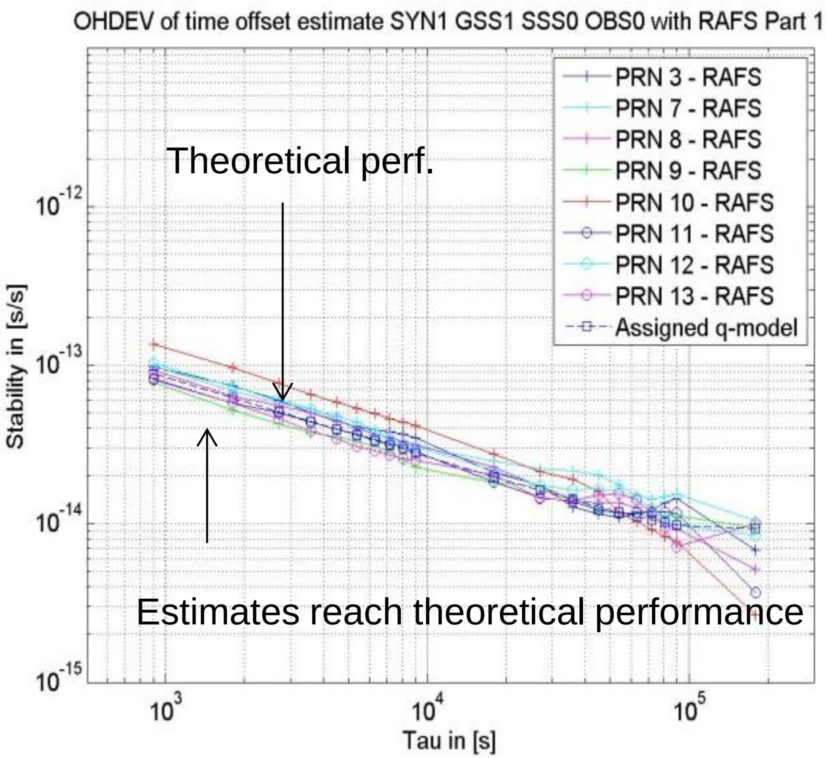


Non-global monitor segment with 41 stations

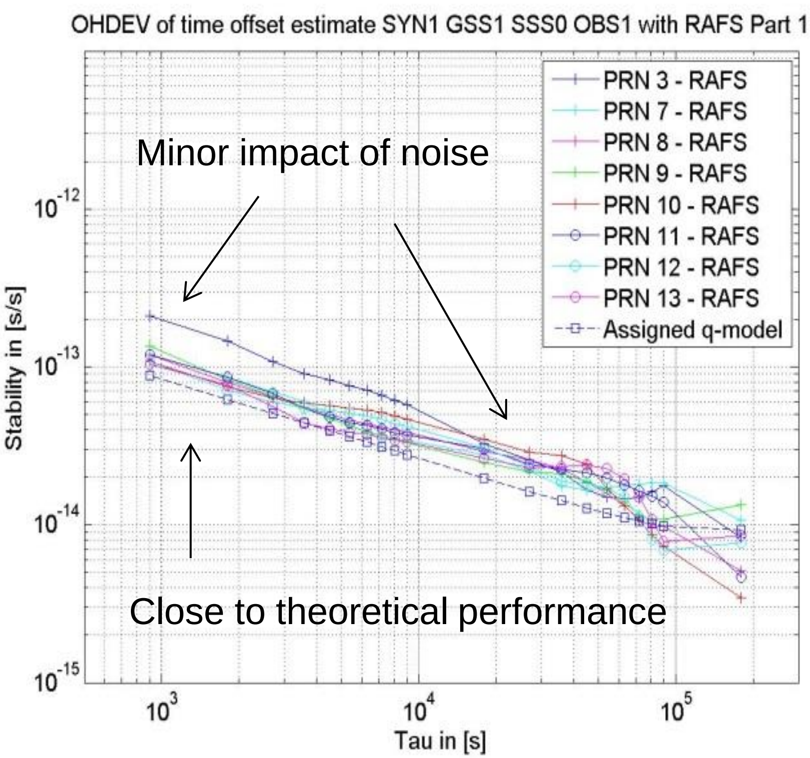
RAFS: Rubidium Atomic Frequency Standard

Satellite Composite Clock Estimates of RAFS

RAFSs Estimates with Observation Noise 0

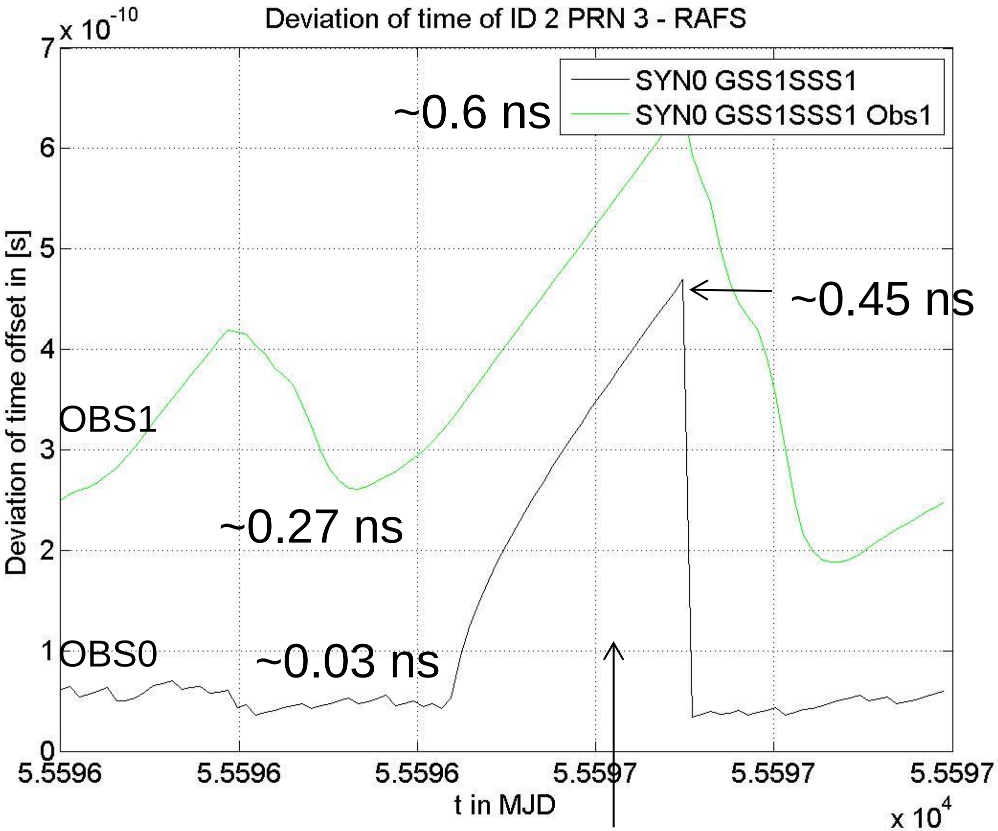


RAFSs Estimates with Observation Noise 1

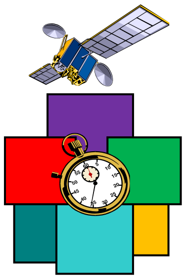


- Satellite Composite Clock more stable than any RAFS

Time Deviation Increases due to Non-observability

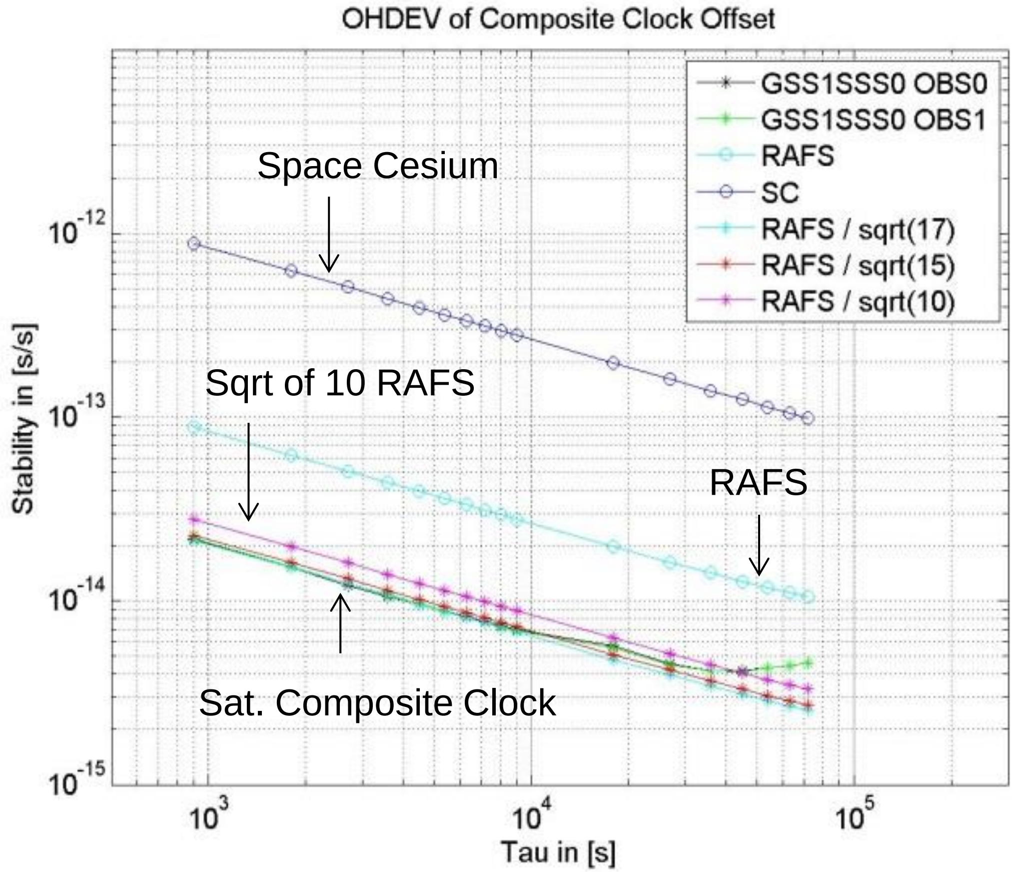


Corrected satellite clock represent composite clock



Increase of synchronization error due to non-observability

Stability of Satellite Composite Clock



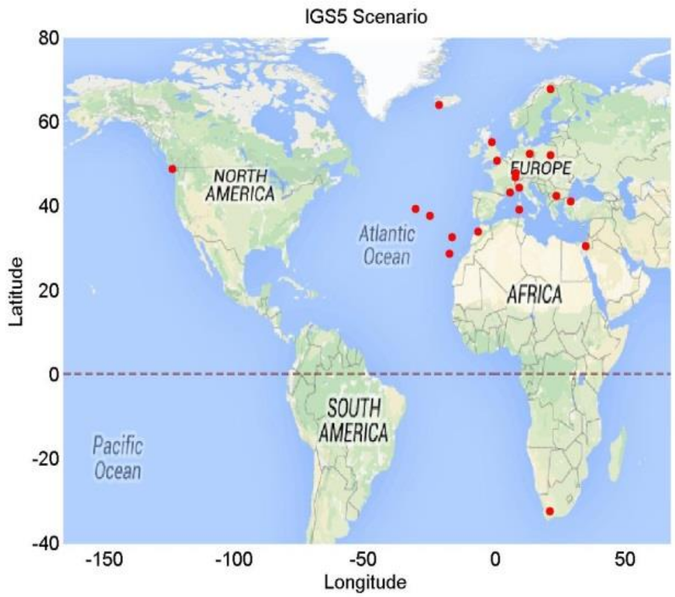
- Satellite composite clock better than square-root of 10 RAFS
- Satellite clocks can be estimated against composite clock

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

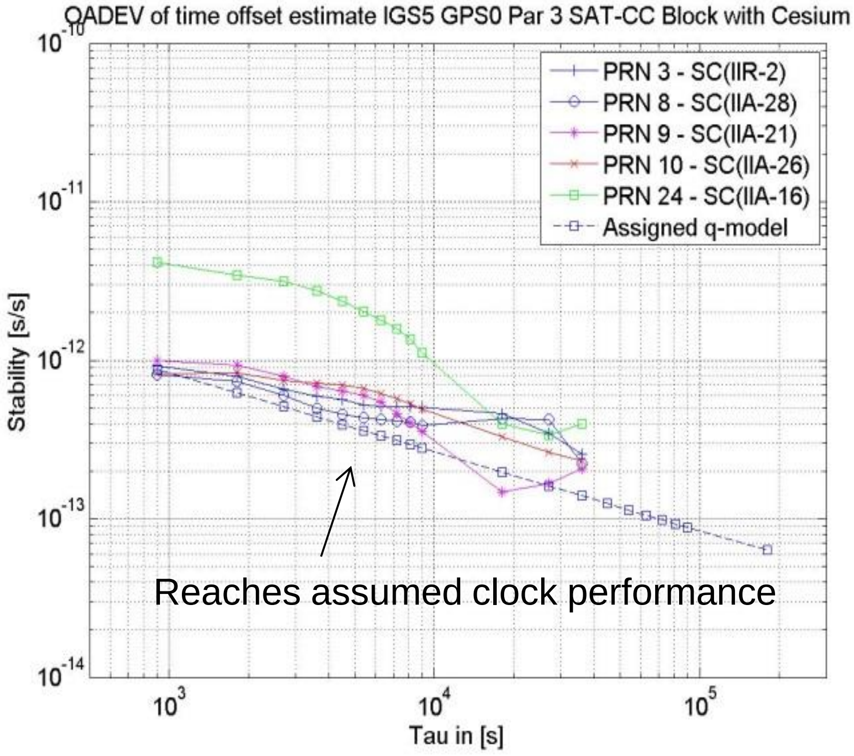
Selection of 20 IGS network stations



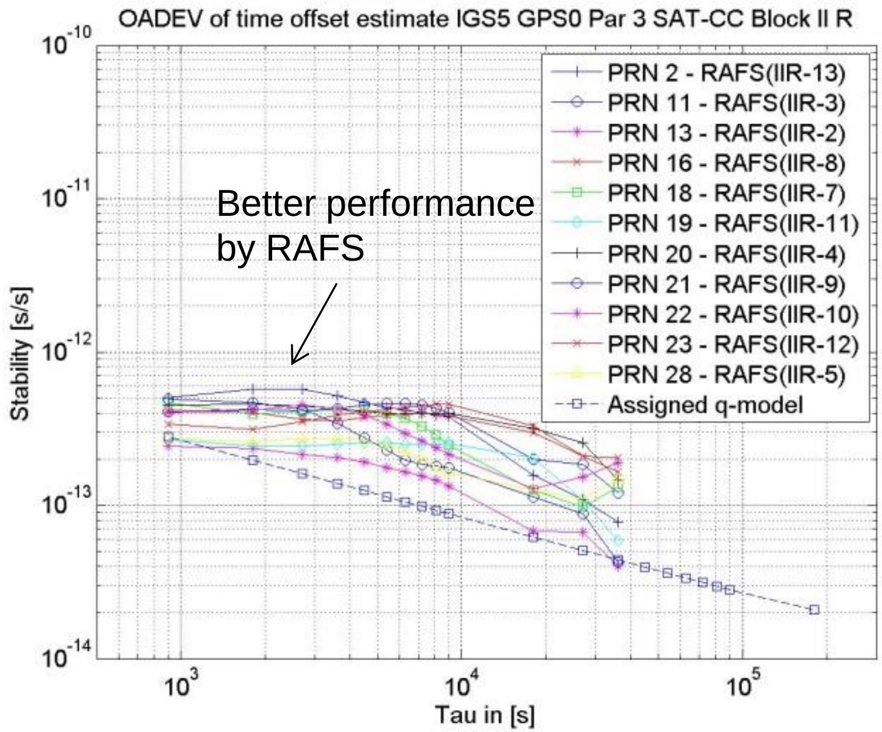
[1] Paper appendix with operational algorithms

Real-Data Verification of GPS Satellite Clocks

Satellites with Space Cesium



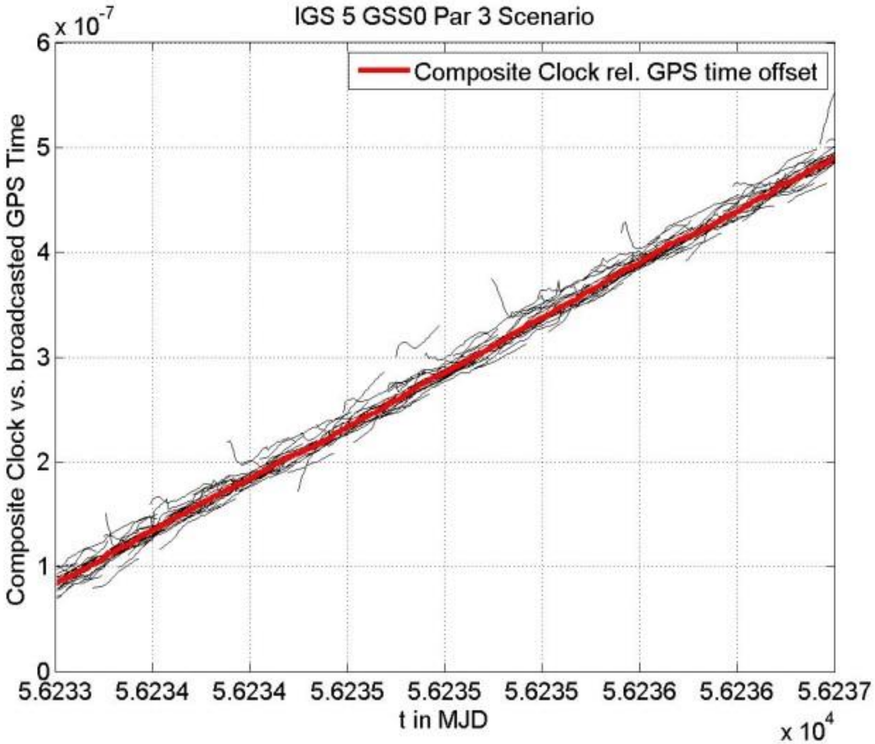
Block IIR with RAFS



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

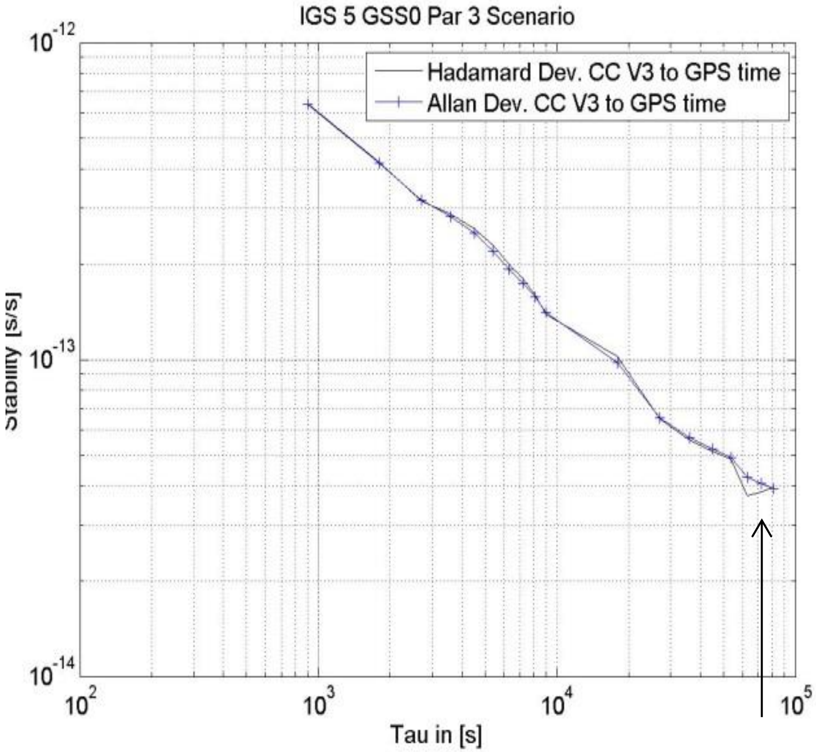
Estimation of Satellite Composite Clock to GPS Time

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