Australian Government
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Precise satellite clock estimation for GPS, BeiDou and Galileo using the Australian Analysis Centre Software

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Introduction

With the continue development of Global Navigation Satellite Systems (GNSS), more effort are encouraged to be participated in International GNSS Service (IGS) to deliver real-time, high quality satellite orbits and clocks, not only for GPS, GLONASS, but also for emerging BeiDou and Galileo for the benefits of global users. Both satellite orbits and clocks play an essential role in precise point positioning. We are developing an analysis centre software aiming at estimating precise satellite orbits and clocks for the four global constellations. This contribution demonstrate the preliminary results that achieved for satellite clock estimation using GPS, BeiDou and Galileo observations. First, the zero-differenced, ionosphere-free mathematical models are introduced. Then, the Kalman filter is implemented to account for the temporal change of the unknown parameters. At last, satellite clocks estimated from both global and regional networks are analysed.

Models

In the first development stage, the zero-differenced, ionosphere-free models are used to eliminate the first order effect of the ionosphere. The mathematical models are given as:

$$E\left(P_{r,IF}^{s}\right) - \rho_r^s = c\left(dt_{r,IF} - dt^{s,IF}\right) + \tau_r^s \tag{1}$$

$$E\left(L_{r,IF}^{s}\right) - \rho_r^s = c\left(dt_{r,IF} - dt^{s,IF}\right) + \tau_r^s + M_r^s \tag{2}$$

with P and L being the code and phase measurements between satellite s and receiver r. Symbol "IF" indicates the ionosphere-free linear combination. Geometric distance ρ is supposed to be known with receiver positions from the IGS SINEX solution and the satellite positions are held fixed using the IGS final orbit products. Then unknown parameters are the biased receiver clock error $dt_{r,IF}$, biased satellite clock error $dt^{s,IF}$, the slant troposphere delay τ_r^s and the ambiguity term M_r^s, which is float. Slant troposphere delay is normally separated into the dry part and wet part. The dry part can be modelled accurately and then is mapped into the slant direction. For the wet part, the zenith wet delay (ZWD) is estimated based on the mapping coefficients. For the other corrections, such as tidal corrections, antenna phase centre offsets and variations, relativity effect, phase-wind-up corrections, differential code biases, they are all considered where applicable. An elevation dependent stochastic model is used to properly weight the measurements, and the code noise is assumed to be 100 times larger than the phase noise.

The above models are applicable to any single CDMA based constellations. In multi-GNSS, extra receiver clock errors are required to be introduced for each constellation. The common parameter in combined mode is the troposphere ZWD. Given the mathematical model and the stochastic model, Kalman filter is used to estimate the unknown parameters in equations (1) and (2), as follows:

$$z_k = Hx_k + v_k \sim (0, R) \tag{3}$$

$$x_k = \Phi x_{k-1} + \varepsilon_k \sim (0, Q) \tag{4}$$

with (3) and (4) being the measurement update equation and time update equation, respectively. The measurement update equation consists of the code and phase measurements in equations (1) and (2), with the corresponding design matrix H. x is the state vector. v is the residual, which is normally distributed with variance-covariance matrix R. Φ is the transition matrix, e.g., an identity matrix. ε is normally distributed with variance-covariance matrix as Q. A pivot receiver is constrained to 0 to remove the rank deficiency in equation (3).

The ambiguities have to be converged to fully exploit the benefit of high-precision carrier phase measurements. Normally the ambiguity term is constant over time and no process noise is needed in the Kalman filter. The receiver clock is changing each epoch and a large process noise is added to account for the unstable receiver clock property. The satellite clock is relatively stable and smaller process noise is used. In summary, the Kalman filter processing details are given as:

Table 1: Kalman filter process noise for the state parameters

Receiver clock	1000m/
Satellite clock	10m
Troposphere zenith wet delay	1mm/$\sqrt{30}$s
Ambiguity	0

Experimental results

One global GPS network and one regional multi-GNSS network are used and their locations are provided in Figure 1. The dates are 29th, March, 2017 and 2018, respectively. An elevation cut-off of 10-degree is applied. The IGS final orbit for GPS, GFZ orbit for multi-GNSS and the daily SINEX file are used to fix the satellite and receiver positions. Cycle slip detection has been enabled. In the first epoch, a least-squares estimation is carried out to derive the initial estimates and their variance-covariance matrix. From the second epoch, Kalman fitler is used to demonstrate the real-time capability.

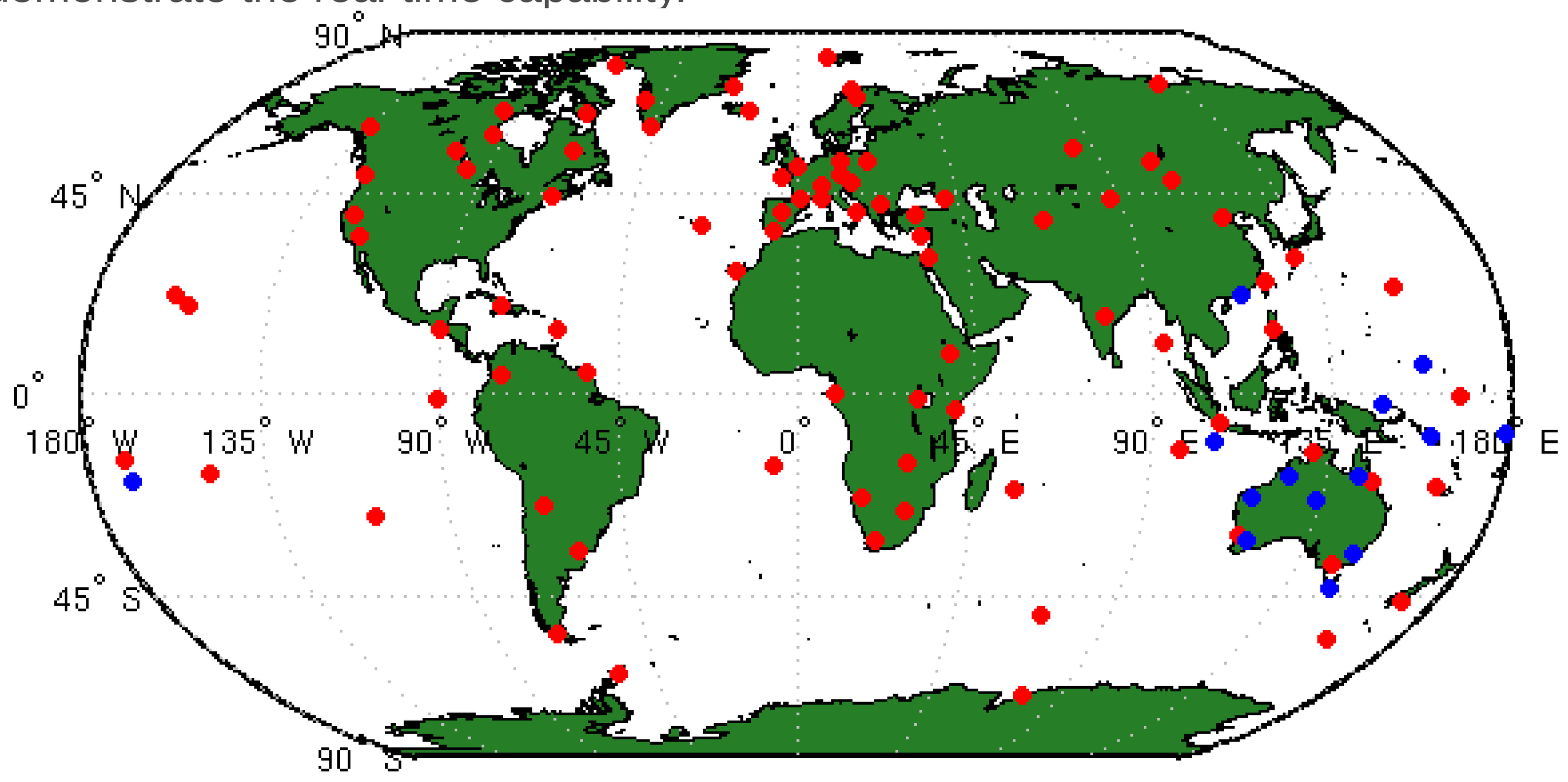

Figure 1: Global (red) and regional (blue) networks used for clock estimation

The global solution for GPS clocks is compared with IGS rapid clock solution using the Analysis Centre Coordinator's (ACC) software. Overall, estimated GPS satellite clock RMS is at 435 pico second (ps) and the standard deviation (STD) is at 220 ps. More specifically, Figure 2 shows the values for individual satellites. The clock RMS is close to the results from CODE, GFZ, etc. However, the clock STD is worse than the other analysis centres, whose is less than 20 ps. The primary reason is that the daily solution requires approximately half an hour to converge. Another reason is the outliers in the observations. The residual statistics show that there are more than 20 epochs with large residual statistics, especially for the first 10 hours. Using the last 12 hours, the clock RMS drops down to 379 ps and the STD reduces to 82 ps. In addition, larger networks will be used to enhance the geometry and increase the number of observations. Note that GPS04 is absent due to unhealthy status. A large RMS is observed for satellite G29.

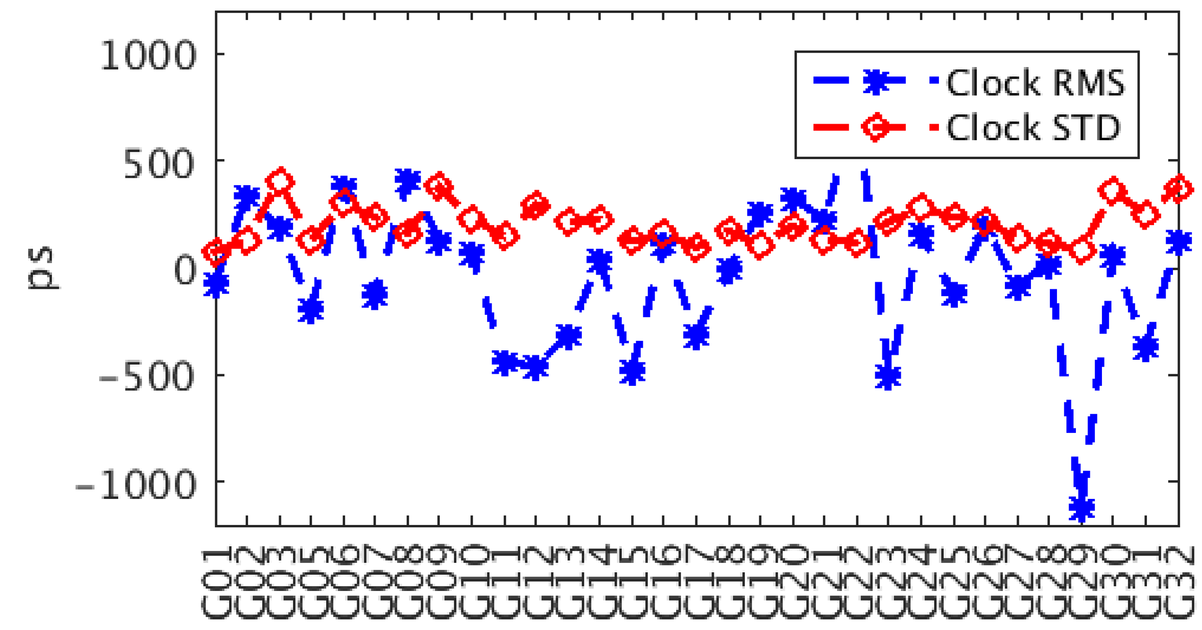

Figure 2: GPS clock RMS and standard deviation

The regional network is used to estimate multi-GNSS clocks in combined mode. The results for satellites C03 and E04 are given in Figure 3 as examples. Comparing with GFZ clock product, after convergence, the estimated clocks for these two satellites behave well. However, we do notice bad results for some BeiDou IGSO and Galileo IOV satellites and we are working on the ways to improve the solution.

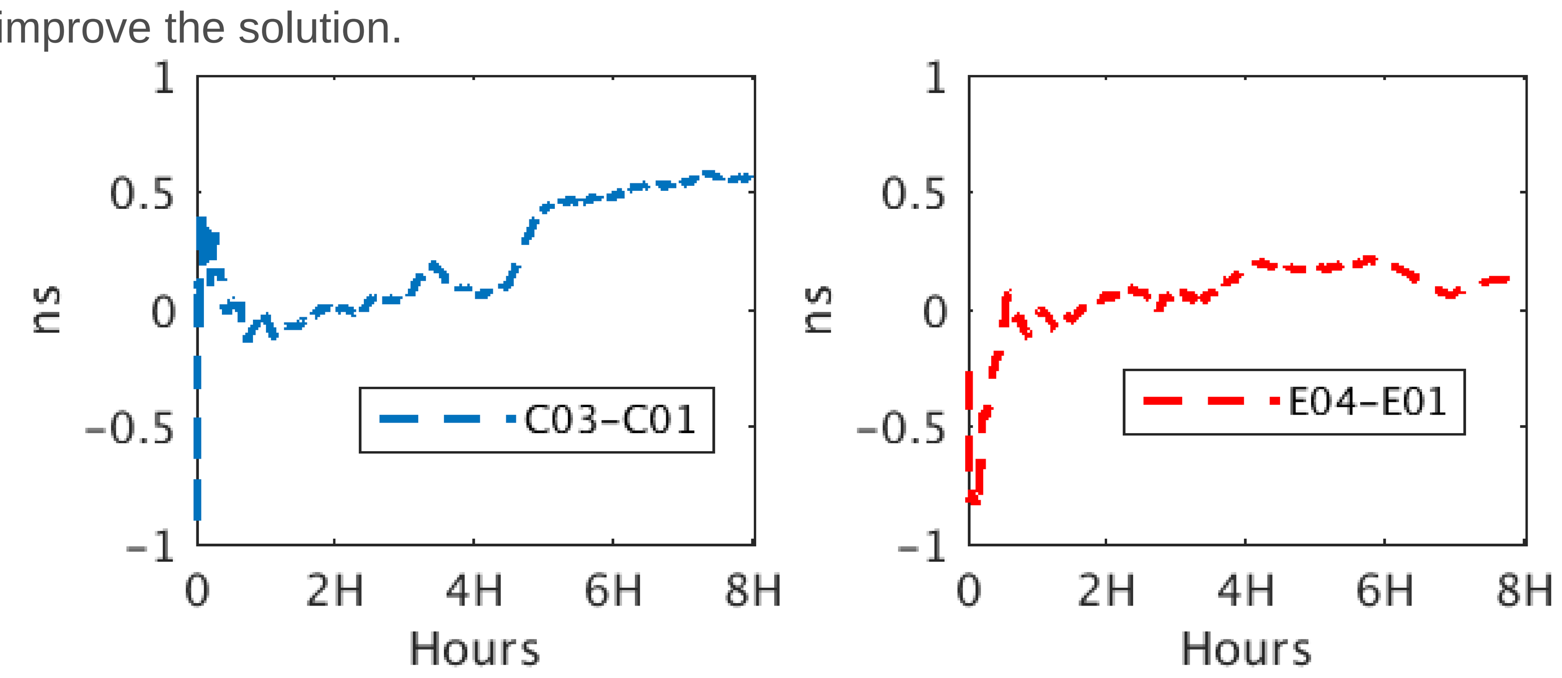

Figure 3: BeiDou C03 and Galileo E04 clock results

Conclusions

Preliminary results have been obtained for precise satellite clock estimation using the Australian Analysis Centre Software. GPS clock results look good, while more work is required to improve the solution for BeiDou and Galileo. Further analysis will continue to be performed and we expect that more precise orbit and clock products will be generated in real-time in the near future.

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