Precise Orbit Determination of GPS Satellites using Carrier Phase Measurements

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Abstract

We have developed a software package to determine high precision GPS satellite orbit and clock, using undifferenced carrier phase measurements at ground stations. In the software, the GPS satellite orbit and clock are estimated by Extended Kalman Filter (EKF). This paper introduces algorithms for the precise determination GPS satellite and clock, including measurement models, precise correction models, satellite orbit models, and the parameter estimation filter. For evaluation, using world-wide 40 IGS (International GPS Service) station observation data, 29 GPS satellite orbits and clocks were determined. A priori satellite position and clock bias were obtained from broadcast ephemerides. Station positions were fixed to the previous week PPP (Precise Point Positioning) results. Compared with IGS Final Orbit and Clock, the estimated satellite position 3D RMS error was 5.2 cm and clock bias RMS error was 0.14 nsec.

搬送波位相観測値を使用した GPS 衛星の高精度軌道決定

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地上局での搬送波位相観測値を使用し GPS 衛星軌道・時計を高精度に決定するためのソフトウェアパッケージを開発した。このソフトウェアでは拡張カルマンフィルタ(EKF)を使って衛星軌道・時計を決定する。本論文では観測モデル、精密補正モデル、衛星運動モデル、及びパラメータ推定フィルタを含んだ精密衛星軌道・時計決定アルゴリズムについて紹介する。評価のため、全世界の IGS 観測局 40 局の観測データを使い、GPS 29 衛星の軌道・時計を決定した。衛星軌道・時計の初期値は放送暦を使用した。観測局位置は前週の精密単独測位 (PPP) による測位解に固定した。IGS 最終暦と比較した推定衛星位置の 3D RMS 誤差は 5.2 cm、同じく時計バイアスの RMS 誤差は 0.14 nsec であった。

1. Introduction

Precise Orbit Determination (POD) of GPS satellites is a key technology for accurate positioning with GPS. As well as satellite orbit, it is necessary to provide the precise satellite clock for PPP (Precise Point Positioning) [1], that has been recently utilized for some positioning applications such as Global Area DGPS. The POD technique for GPS satellites can also be applied to POD of LEO (Low Earth Orbit) satellites equipped with GPS receivers.

For precise GPS satellite orbit and clock determination as well as accurate positioning with GPS, we have developed a high-functional and precise analysis software package GpsTools (GT), that mainly uses GPS carrier phase measurements as basic observables.

At first, this paper will introduce the algorithms for the precise GPS satellite orbit and clock determination incorporated in GT, including measurement models, precise correction models, satellite orbit models, and the parameter estimation filter.

Secondly, we will show the accuracy evaluation results of the estimated GPS satellite orbit and clock by GT, using observation data obtained from the world-wide ground GPS station network, compared with IGS precise products.

2. Algorithms

2.1 Measurement Model

The basic observable for the precise GPS satellite orbit and clock determination is the undifferenced ionosphere-free LC (Linear Combination) of L1/L2 carrier phases, shown as Φ_{LC} in eq. (1). The ionospheric delay in the original observable is eliminated by LC of dual-frequency carrier phases.

$$\Phi_{LC} = C1\lambda_1\Phi_{L1} + C2\lambda_2\Phi_{L2}$$
$$= \rho + c(dt - dT) + T + N_{LC} \quad (1)$$
$$- \Delta_{pcvs} - \Delta_{pcvr} + \Delta_{rel} + \Delta_{phw} + \varepsilon_{LC}$$
$$C1 = f_1^{\,2}/(f_1^{\,2} - f_2^{\,2}) \quad C2 = -f_2^{\,2}/(f_1^{\,2} - f_2^{\,2})$$

λ_1, λ_2 : L1/L2 carrier wave length (m)
f_1, f_2 : L1/L2 carrier frequency (Hz)
Φ_{L1}, Φ_{L2} : L1/L2 carrier phase mesurement (cycle)
ρ : satellite-station geometric distance (m)
dt, dT : receiver/satellite clock bias (sec)
T : tropospheric delay (m)
N_{LC} : carrier phase bias of ion-free LC (m)
$\Delta_{pcvs}, \Delta_{pcvr}$: satellite/receiver antenna PCV (m)
Δ_{rel} : relativity effect correction (m)
Δ_{phw} : phase-windup effect correction (m)
ε_{LC} : mesurement noise of ion-free LC (m)

The satellite-station geometric distance ρ in eq. (1) is obtained by solving so-called light-time equation expressed as eq. (2). This equation contains the satellite movement effect during signal propagation and the received time offset by the receiver clock bias. In eq. (2), the satellite position is represented in inertial coordinate (ECI) and the station position and so on, prime (') attached, in earth-fixed (ECEF).

$$\rho = \left| \boldsymbol{r}^s(t - dt - \rho/c) + \boldsymbol{\Delta}_{apcs} - \boldsymbol{U}(t - dt)^T (\boldsymbol{r}_r' + \boldsymbol{\Delta}_{sdisp}' + \boldsymbol{\Delta}_{apcr}') \right| \quad (2)$$

$\boldsymbol{r}^s(t)$: satellite s position (m)
$\boldsymbol{r}_r'$: station r position (m)
$\boldsymbol{U}(t)$: ECI to ECEF transformation matrix
$\boldsymbol{\Delta}_{apcs}, \boldsymbol{\Delta}_{apcr}'$: satellite/receiver antenna offset (m)
$\boldsymbol{\Delta}_{sdisp}'$: station displacement (m)

Between earth-fixed and inertial, coordinate can be interconnected by the transformation matrix $\boldsymbol{U}(t)$ computed by the precession/nutation model and ERP (Earth Rotation Parameters) expressed as eq. (3). Table 1. shows the reference frames and these inerconnection supported by GT. For details, refer to [2].

$$\boldsymbol{U}(t) = \boldsymbol{R}_y(-x_p)\boldsymbol{R}_x(-y_p)\boldsymbol{R}_z(GAST)\boldsymbol{N}(t)\boldsymbol{P}(t) \quad (3)$$
$$GAST = GMST + \Delta\psi\cos\varepsilon$$
$$GMST = GMST(0^h UT1) + r(t_{UTC} + (UT1 - UTC))$$

$\boldsymbol{N}(t), \boldsymbol{P}(t)$: nutation/precession matrix
$\boldsymbol{R}_x, \boldsymbol{R}_y, \boldsymbol{R}_z$: coordinate rotation matrix around x/y/z axis
$GAST$: Greenwich Apparent Sidereal Time
$GMST$: Greenwich Mean Sidereal Time
x_p, y_p : celestial pole offsets
$UT1 - UTC$: earth rotation angle offset
$\Delta\psi, \varepsilon$: nutation in longitude, obliquity
r : ratio of universal to sidereal time

Table 1. Reference Frames and Interconnection

Item	Models
Earth Fixed	ITRF2000 (IGS00, IGb00)
Inertial	ICRF
Precession/ Nutation	IAU1976 Precession IAU1980 Nutation with dpsi/deps or IERS1996 Nutation
Earth Rotation Parameters	IERS Bulletin B, EOP C04, IGS ERP or Estimated

Because of the difference of signal propagation time and receiver clock biases, signal transmision time at satellites are slightly different. So the satellite positions $\boldsymbol{r}^s$ in all equations have to expressed using a common time frame t, usually according to GPS Time. As signal propagation time plus receiver clock bias Δt does not exceed 0.1 sec at the GPS satellite orbit, the time synchronization can be approximated as eq. (3), only considering the satellite velocity and the earth point-of-mass gravity. The partial derivative of Φ_{LC} by the satellite position at t is also formed as eq. (4) using the satellite position transition matrix.

$$\boldsymbol{r}^s(t - \Delta t) \approx \boldsymbol{r}^s(t)\left(1 - \frac{GM_E}{2r^s(t)^3}\Delta t^2\right) - \boldsymbol{v}^s(t)\Delta t \quad (3)$$
$$\Delta t = dt + \rho / c$$
$$\frac{\partial \Phi_{LC}}{\partial \boldsymbol{r}^s(t)} = \frac{\partial \rho}{\partial \boldsymbol{r}^s(t)} = \frac{\partial \rho}{\partial \boldsymbol{r}^s(t - \Delta t)} \boldsymbol{\Phi}_{rr}(t - \Delta t, t) \quad (4)$$
$$\frac{\partial \rho}{\partial \boldsymbol{r}^s(t - \Delta t)} = \frac{\left(\boldsymbol{r}^s(t - \Delta t) + \boldsymbol{\Delta}_{ants} - \boldsymbol{U}(t - dt)^T (\boldsymbol{r}_r' + \boldsymbol{\Delta}_{sdisp}' + \boldsymbol{\Delta}_{antr}')\right)^T}{\rho}$$
$$\boldsymbol{\Phi}_{rr}(t - \Delta t, t) \approx \boldsymbol{I}_{3\times3} - \frac{GM_E}{2r^s(t)^3}\left(\boldsymbol{I}_{3\times3} - \frac{3\boldsymbol{r}^s(t)\boldsymbol{r}^s(t)^T}{r^s(t)^2}\right)\Delta t^2$$

GM_E : earth gravitational coefficient
$\boldsymbol{v}^s(t)$: satellite s velocity at time t (m)
$\boldsymbol{\Phi}_{rr}(t, t_0)$: satellite position transition matrix t_0 to t

Eq. (2) including eq. (3) can be solved by the successive iteration with initial guess parameters. The receiver clock bias dt, that only requires the accuracy of about 100 nsec, is determined by the conventional point positioning with pseudo-range observables and broadcast ephemerides.

The tropospheric delay T in eq. (2) is expressed as eq. (5) with tropospheric parameters ZTD, G_E, G_N and the mapping function. At this time, a widely used mapping function for GPS analysis is NMF [3] that provides adequate accuracy even at the low elevation angle without any meteorological parameters.

$$
\begin{aligned}
T &= M_{dry}(El)ZHD \\
&\quad + M_{wet}(El)(1 + G_E g_E + G_N g_N)(ZTD - ZHD) \\
&\quad ZHD = 0.0022768 P_0 /(1 - 0.00266\cos 2\phi - 0.00028 H) \\
&\quad g_E = \cot El \sin Az \quad g_N = \cot El \cos Az
\end{aligned}
\tag{5}
$$

ZTD : tropospheric Zenith Total Delay (m)
ZHD : tropospheric Zenith Hydrostatic Delay (m)
G_E, G_N : tropospheric horizontal gradient parameters
M_{dry}, M_{wet} : dry and wet term of mapping function
Az, El : azimuth and elevation angle of satellite
P_0 : pressure at mean sea-level (hPa)
ϕ, H : station latitude and height (m)

Another precise measurement correction terms in eq. (2) and (3) are antenna offsets and its variations. The satellite antenna offset and Phase Center Variation (PCV) are shown as eq. (6), representing the satellite antenna offset with respect to the satellite center-of-mass and the PCV depending on the nadir angle. GT uses the fixed antenna offset determined by IGS. The satellite antenna PCVs are estimated by the long period stacking of postfit residuals in estimations. Example of satellite antenna PCV and postfit resduals stacking is shown in Figure 1.

$$
\boldsymbol{\Delta}_{apcs} = \boldsymbol{E}_{sat\rightarrow eci}\boldsymbol{\Delta}_{satao} \quad \Delta_{pcvs} = \Delta_{pcvs}(\theta) \tag{6}
$$

$\boldsymbol{E}_{sat\rightarrow eci}$: transformation satellite-fixed to inertial
$\boldsymbol{\Delta}_{satao}$: antenna offset in satellite-fixed coordinate
θ : nadir angle to ground station

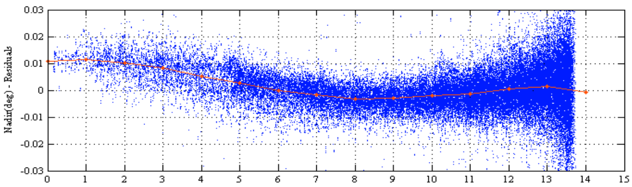

Figure 1. PRN22 Satellite Antenna PCV (red line) and Postfit Residuals Stacking (blue dots)

The receiver antenna offset and PCV corrections are shown as eq. (7). The receiver antenna offset parameters are determined by the ground calibration process and are formed as a PCV table for each antenna type. GT uses the standard antenna PCV table provided by IGS.

$$
\begin{aligned}
\boldsymbol{\Delta}_{apcr}' &= \boldsymbol{E}_{local\rightarrow ecef}\left(\boldsymbol{\Delta}_{ecc} + C1\boldsymbol{\Delta}_{apcr1} + C2\boldsymbol{\Delta}_{apcr2}\right) \\
\Delta_{pcvr} &= C1\Delta_{pcvr1}(El) + C2\Delta_{pcvr2}(El)
\end{aligned}
\tag{7}
$$

$\boldsymbol{E}_{local\rightarrow ecef}$: transformation station-local to earth-fixed
$\boldsymbol{\Delta}_{ecc}$: marker to ARP offset (m)
$\boldsymbol{\Delta}_{apcr1}, \boldsymbol{\Delta}_{apcr2}$: ARP to L1/L2 phase center offset (m)
$\Delta_{pcvr1}, \Delta_{pcvr2}$: L1/L2 phase center variation (m)

The station position displacement caused by earth tides is shown as eq. (8). The earth tides include solid earth tide, ocean loading, and polar tide. Very precise models for the station displacement are established by previous many works. For detailed models of the station displacement, refer to [2].

$$
\boldsymbol{\Delta}_{sdisp}' = \boldsymbol{E}_{local\rightarrow ecef}(\boldsymbol{\Delta}_{solid} + \boldsymbol{\Delta}_{ocean} + \boldsymbol{\Delta}_{polar} + \ldots) \tag{8}
$$

$\boldsymbol{\Delta}_{solid}$: displacement by solid earth tide (m)
$\boldsymbol{\Delta}_{ocean}$: displacement by ocean loading (m)
$\boldsymbol{\Delta}_{polar}$: displacement by polar tide (m)

The other precise corrections in the measurement model are the relativistic and the phase wind-up effect. The periodic variation of the satellite clock is shown by the relativistic effect expressed as eq. (9). GPS Right Circularly Polarized (RCP) wave phase is affected by the relative rotation between satellite and receiver antennas, that is called phase wind-up, expressed as eq. (10).

$$
\Delta_{rel} = -2\boldsymbol{r}^s \cdot \boldsymbol{v}^s / c \tag{9}
$$

$$
\begin{aligned}
\Delta_{phw} &= (C1\lambda_1 + C2\lambda_2)\cos^{-1}(\boldsymbol{D}\cdot\boldsymbol{D}'/|\boldsymbol{D}||\boldsymbol{D}'|) \\
\boldsymbol{D} &= \boldsymbol{x} - \boldsymbol{k}(\boldsymbol{k}\cdot\boldsymbol{x}) + \boldsymbol{k}\times\boldsymbol{y} \\
\boldsymbol{D}' &= \boldsymbol{x}' - \boldsymbol{k}(\boldsymbol{k}\cdot\boldsymbol{x}') - \boldsymbol{k}\times\boldsymbol{y}'
\end{aligned}
\tag{10}
$$

$\boldsymbol{D}, \boldsymbol{D}'$: effective dipole vectors of satellite/receiver
$\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}$: local receiver unit vectors (east, north, up)
$\boldsymbol{x}', \boldsymbol{y}', \boldsymbol{z}'$: satellite body coordinate unit vectors
$\boldsymbol{k}$: satellite to receiver unit vector

Table 2. shows the detail of the precise measurement corrections provided by GT.

Table 2. Precise Measurement Corrections

Item		Models
Satellite Antenna Offset and PCV		Block II/IIA: (0.279,0,1.023) m Block IIR: (0,0,0) m PCV wrt Nadir Angle
Receiver Antenna Offset and PCV		IGS_01.PCV
Phase-windup Effect		Wu model
Relativity Effects		Satellite Clock Variation
Station Displace-ment	Solid Earth Tide	IERS Conventions 1996 Ch.7 Step 1: in-phase degree 2-3, out-of-phase, latitude dependence Step 2: contribution from the diurnal band : K1 only
	Ocean Loading	IERS Conventions 1996 Ch.7, NAO.99b (GOTIC2)
	Polar Tide	IERS Conventions 1996 Ch.7
ERP variation		Sub-daily Variation by Ray Model

2.2 Satellite Orbit Model

Figure 2. shows the magnitude of perturbations at satellite orbit depending on its height. For the precise satellite orbit determination, accelerations more than 10^{-10} m/sec^2 have to be taken into account. So at the GPS satellite orbit, the orbit model has to include the geopotential up to degree 8 with tidal effects, sun/moon gravity, Solar Radiation Pressure (SRP), and relativity.

The satellite orbit model is expressed as eq. (11), that is the ordinary differential equation of the satellite position and velocity. Detailed formulations of each term are found in [4]. The state transition is computed by a numerical integration of the equation. Table 3. shows the precise satellite orbit models supported by GT.

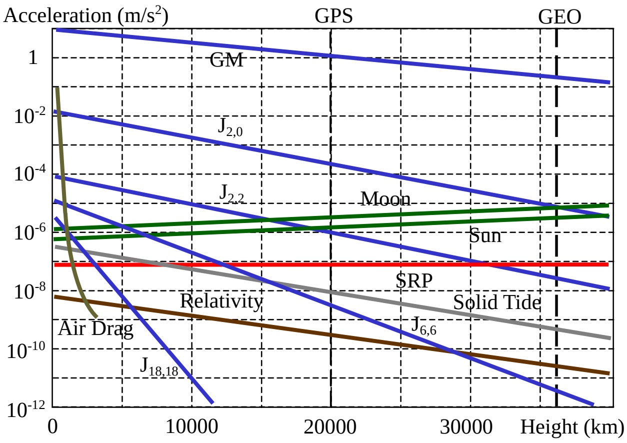

Figure 2. perturbation at satellite orbit

$$\dot{\boldsymbol{r}}^s = \boldsymbol{v}^s$$
$$\dot{\boldsymbol{v}}^s = -\frac{GM_E \boldsymbol{r}^s}{r^3} + \boldsymbol{a}_{geop} + \boldsymbol{a}_{3rdbody} + \boldsymbol{a}_{srp} + \boldsymbol{a}_{rel} + \dots \tag{11}$$

$\boldsymbol{a}_{geop}$: geopotential accelaration correction (m/sec^2)
$\boldsymbol{a}_{3rdbody}$: 3rd body gravity accelaration (m/sec^2)
$\boldsymbol{a}_{srp}$: SRP accelaration (m/sec^2)
$\boldsymbol{a}_{rel}$: accelaration by relativistic effect (m/sec^2)

Table 3. Precse Satellite Orbit Models

Item		Models
Geopotential		JGM-3 up to degree 12 with Tidal Effect Corrections
Tidal Effect	Solid Earth Tide	IERS Conventions 1996 Ch.6 frequency independent: degree 2,3 frequency dependent: K1 only
	Ocean Tide	IERS Conventions 1996 Ch.6 8 constituents, degree 2,3 (CSR2.0)
	Polar Tide	IERS Conventions 1996 Ch.6
3rd Body Gravity		Moon and Sun as point of mass
Planetary Ephemeris		JPL DE 405
Solar Radiation Pressure Model		cannonball, ROCK4/42 (T10/T20), CODE RPR or GSPM.04b
Eclipse Model		cylidric or penumbra/umbra by earth and moon shadow
Relativistic Effect		IERS Conventions 1996 Ch.11

2.3 Other State Transition Models

The other state transitions are modeled as follows, satellite clock : 1st order Gauss-Marcov, receiver clock : white-noise, tropospheric parameters : random-walk, and ERP : random-walk. The carrier phase bias is considered as a fixed value in a arc. If detecting a cycle-slip in the arc, the estimated phase bias is reinitialized.

2.4 Parameter Estimation

For parameter estimation, GT employs Extended Kalman Filter expressed in eq. (12) as the observation update and eq. (13) as the temporal update. In addition to the conventional forward filter, the backward filter and the smoother are supported by GT. The details of Kalman filter formulation are found in [5].

$$\begin{aligned} \boldsymbol{K}_k &= \boldsymbol{P}_k(-)\boldsymbol{H}_k^T(\boldsymbol{H}_k\boldsymbol{P}_k(-)\boldsymbol{H}_k^T + \boldsymbol{R}_k)^{-1} \\ \hat{\boldsymbol{x}}_k(+) &= \hat{\boldsymbol{x}}_k(-) + \boldsymbol{K}_k(\boldsymbol{z}_k - \boldsymbol{h}(\hat{\boldsymbol{x}}_k(-))) \\ \boldsymbol{P}_k(+) &= (\boldsymbol{I} - \boldsymbol{K}_k\boldsymbol{H}_k)\boldsymbol{P}_k(-) \end{aligned} \tag{12}$$

$$\begin{aligned} \hat{\boldsymbol{x}}_{k+1}(-) &= \hat{\boldsymbol{x}}_k(+) + \int_{t_k}^{t_{k+1}} \boldsymbol{f}(\hat{\boldsymbol{x}}_k(+),\tau)d\tau \\ \boldsymbol{P}_{k+1}(-) &= \boldsymbol{\Phi}(t_{k+1},t_k)\boldsymbol{P}_k(+)\boldsymbol{\Phi}(t_{k+1},t_k)^T + \boldsymbol{Q}_k \end{aligned} \tag{13}$$

For the GPS satellite orbit and clock determination, the estimated state vector, in the Kalman Filter form, consisting of the satellite position and velocity, satellite clock, receiver clock, tropospheric parameters. Additionally satellite SRP parameters and ERP are incorporated if necessary. In the estimation, the satellite and receiver clocks are treated as the relative clock to the reference clock station by fixing the reference clock to 0.

The state vector $\hat{x}_k$ at epoch t_k is sequentially obtained with an input of the measurement vector z_k by Kalman Filter estimation process.

3. Evaluation of Accuracy

3.1 Estimation Conditions

To evaluate the accuracy of the GPS satellite orbit and clock determination, using world-wide 40 IGS station observation data, 29 GPS satellite orbit and clock are estimated. Figure 3. shows the geometry of the station network used for the evaluation. The other estimation settings are summarized in Table 4. Satellite SRP parameters, receiver clocks, tropospheric parameters and Earth Rotation Parameters are estimated in the same time. All estimated parameters per an epoch are shown in Table 5.

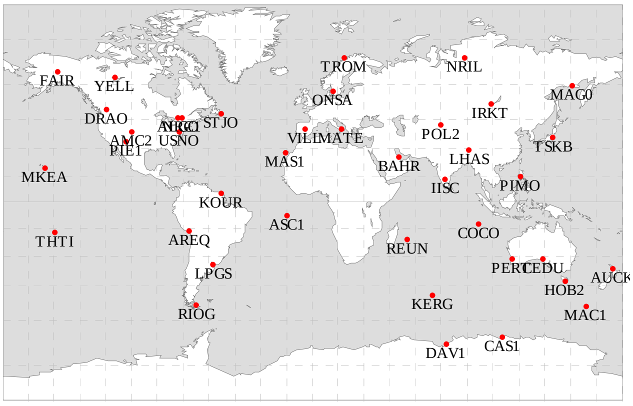

Figure 3. Station Network used for evaluation

Table 4. Summary of Estimation Settings

Item	Setting
Analysis Software	GT ver.0.5.5
Estimation Time Span	GPS Week 1291 (2004/10/3-10/9)
Filter Pass	3 Pass Filter/Smoother
Estimation Unit Time	24H+Overlap 24H, Interval 300sec
Initial Orbit/Clock	Broadcast Ephemeris
Station Positions	Fixed to Previous Week PPP
Tropospheric Model	Saastamoinen
Mapping Function	NMF
Min. Elevation	10 deg
Reference Clock	AMC2

Table 5. Estimated Parameters per an Epoch

Parameters	Number of States	Sats/ Stas	Total
Satellite Position/Velocity	6	29	174
Satellite SRP Parameters	4	29	116
Satellite Clock	2	29	58
Station Tropos. ZTD	1	40	40
Station Tropos. Gradient	5	40	200
Station Receiver Clock	1	40	40
Carrier Phase Bias	1	29 x 40	1160
Earth Rotation Parameters	3	1	3
Total Parameters per Epoch			1788

3.2 Accuracy of Orbit

Under the conditions described above, the GPS satellite orbit and clock are determined using GT. The estimation results are compared with the IGS Final Orbit and Clock. IGS Final Orbit and Clock are determined using the IGS world-wide GPS station network, as the weighted averages of 8 AC (Analysis Center) solutions, eg. CODE, ESA, GFZ, JPL, NRCan, MIT, NOAA, SOPAC. Each AC utilizes various precise analysis software package. The formal accuracy is stated below 5 cm as the orbit and below 0.1 nsec as the clock.

Table 6. shows the estimated satellite orbit accuracy with respect to IGS Final Orbit, as the average of all satellite position RMS errors. Figure 4. shows the error of each satellite and Figure 5. shows the time sequence of the PRN01 satellite position 3D and radial/along-track/cross-track error as an example.

Table 6. Satellite Orbit Accuracy

	3D	Radial	Along-Track	Cross-Track
Position RMS Error	5.18 cm	1.97 cm	3.43 cm	3.12 cm

Avarage of 29 satellites, wrt IGS Final

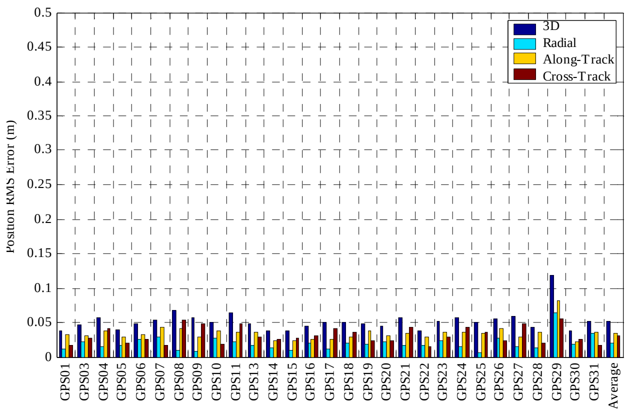

Figure 4. Estimated Orbit Error of Each Satelite

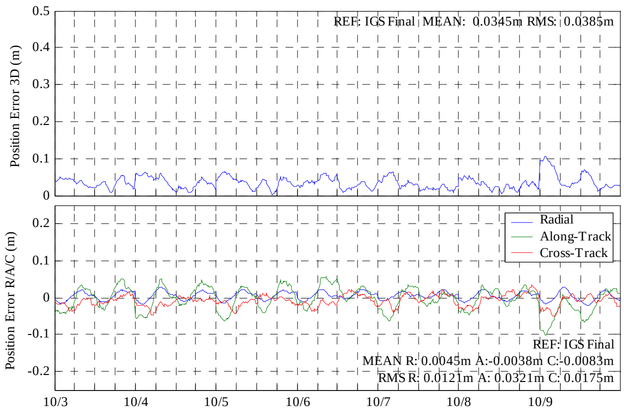

Figure 5. PRN01 Position Error Time Sequence (upper : 3D, lower : Radial/Along-Trk/Cross-Trk)

3.3 Accuracy of Clock

Table 7. shows the estimated satellite clock accuracy compaired with IGS Final Clock, as the average of all satellite clock bias RMS errors. The estimated clock is relative value to the reference clock station, so relative values to the mean satellite clocks are compared with IGS. Figure 6. shows the error of each satellite.

Table 7. Estimated Clock Accuracy

	With BIAS	Without BIAS
Clock Bias RMS Error	0.135 ns	0.099 ns

Avarage of 29 satellites, wrt IGS Final

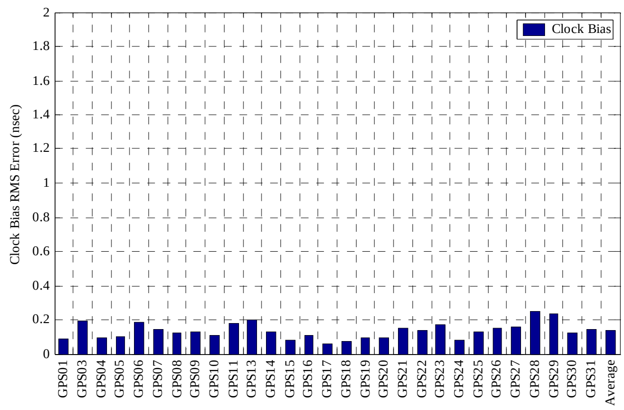

Figure 6. Estimated Clock Error of Each Satellite

3.4 Other Evaluations

Table 8. shows the comparison with the accuracies of IGS AC orbit and clock solutions under the same conditions. Generally speaking, the orbit and clock by GT has almost the same level accuracy compared with IGS ACs.

To investigate the dependency of the accuracy to the station network geometry, the orbit and clock estimated using diffenent numbers of stations. The result is shown in Table 9.

Table 8. Comparison with IGS AC Solutions

Orbit/Clock		Analysis S/W	RMS Error	
			Orbit	Clock
GT 3 pass		GpsTools ver.0.5.5	5.2 cm	0.14 ns
IGS AC	CODE	Bernese ver.5.0	3.3 cm	0.11 ns
	NRCan	GIPSY/OASIS-II	3.8 cm	0.10 ns
	ESOC	BAHN,GPSOBS etc	14.2 cm	0.13 ns
	GFZ	EPOS.P.V2	3.1 cm	0.09 ns
	JPL	GIPSY/OASIS-II	5.5 cm	0.15 ns
	MIT	GAMIT/GLOBK	5.3 cm	0.31 ns
	NOAA	page5	9.9 cm	—
	SOPAC	GAMIT/GLOBK	7.5 cm	—

Avarage of 29 satellites, wrt IGS Final

Table 9. Station Geometry Dependency

	8 Stations	12 Stations	24 Stations
Orbit Error	12.3 cm	7.7 cm	5.7 cm
Clock Error	0.25 ns	0.20 ns	0.16 ns

4. Conclusions

The algorithms for the precise GPS satellite oribit and clock determination and the accuracy evaluation result using the precise analysis software GT are described.

Compared with IGS Final Orbit and Clock, the estimation result shows the accuracy of 5.2 cm as the satellite position 3D RMS error and 0.14 nsec as the clock bias RMS error.

References

[1] J.F.Zumberge et al., Precise point positioning for the efficient and robust analysis of GPS Data from large networks, J.Geophys.Res., 102B3, 5005-5018, 1997

[2] D.D.McCarthy, IERS Technical Note 21, IERS Conventions (1996), July 1996

[3] A.E.Niell, Global mapping Functions for the atmosphere delay at radio wavelengths, J.Geophys. Res., 101B2, 3227-3246, 1996

[4] O.Montenbruck et al., Satellite Orbits : Models, Methods, and Applications, Springer, 2000

[5] A.Gelb et al., Applied Optimal Estimation, The M.I.T Press, 1974