JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 39, No. 5, September–October 2002

Orbit Determination of Spacecraft Using Global Positioning System Single-Frequency Measurement

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The dynamic orbit determination of a low Earth orbiter using global positioning system single-frequency measurements has been implemented. Currently two methods are being applied to eliminate or reduce ionospheric path delay in single-frequency measurement. One is a group and phase ionosphere calibration technique using code pseudorange and L1 carrier phase, and the other is application of total electron content values from an ionospheric model using only L1 carrier phase to determine the orbit. A new method based on the latter has been developed, which estimates the scale factors of total electron content values in the location of a low Earth orbiter once per each measurement time. Orbit determination using actual global positioning system measurements of the TOPEX/POSEIDON and the Challenging minisatellite payload was conducted to verify the accuracy of the new method. It is verified that, if the total electron content's scale factor estimation technique were applied, 1-m level position accuracy (1σ) for low Earth orbit below 500-km altitudes could be achieved using precision orbit determination based on the global positioning system double-differencing method.

Nomenclature

$\bar{a}_{ACR}$ = empirical general accelerations with nine scale factors, m/s^2
C_{iu}^{jk} = double-differenced phase ambiguity, m
DD_{iu}^{jk} = explicit double-differenced carrier-phase converted range measurement model, m
f = frequency, Hz
t_i, δt_i = tagging time of measurement and receiver clock error at ith ground receiver, respectively, s
t_u, δt_u = tagging time of measurement and receiver clock error at onboard receiver of the low Earth orbiter, respectively, s
u = argument of latitude of the satellite, rad
α_A, β_A, γ_A = along-track parameters of empirical general acceleration
α_C, β_C, γ_C = cross-track parameters of empirical general acceleration
α_R, β_R, γ_R = radial parameters of empirical general acceleration
$\delta\rho_i^j$ = sum of propagation delays from jth global positioning system (GPS) satellite to ith ground receiver, m
$\delta\rho_u^j$ = sum of propagation delays from jth GPS satellite to onboard receiver of the low Earth orbiter, m
$\varepsilon_{\rm grp}$, $\varepsilon_{\rm ph}$ = receiver instrument noise of code and phase, respectively, m
ν = scale factor of total electron content value
ρ_i^j, $\dot{\rho}_i^j$ = geometric line-of-sight range and range rate between jth GPS satellite and ith ground receiver, respectively, m, m/s
ρ_u^j, $\dot{\rho}_u^j$ = geometric line-of-sight range and range rate between jth GPS satellite and onboard receiver of the low Earth orbiter, respectively, m, m/s
$\tau_{\rm grp}$, $\tau_{\rm ph}$ = total path delay of code and carrier phase, respectively, m
τ_0 = common delay caused by geometry and factors other than the ionosphere, m

Introduction

THE main mission of the Republic of Korea multipurpose satellite-2 (KOMPSAT-2), which will be launched in 2004, is construction of the three-dimensional cartography of the Korean peninsula by utilizing multispectral camera images with panchromatic 1-m resolution. The KOMPSAT-2 will be operated on a circular sun-synchronous orbit of 685 ± 1 km altitude, and its mission requirement of orbit determination is 1-m (1σ) in position. The KOMPSAT-2 will implement the TOPSTAR 3000 global positioning system (GPS) receiver of Alcatel Space Industries in France, which generates the coarse acquisition (C/A) code and L1 carrier phase. The precision orbit determination system using the GPS single-frequency measurements has been developed to satisfy the mission requirement. The software is based on dynamic parameters estimation and is composed of precision perturbation models for the satellites, the GPS measurement models, and a weighted least-squares batch filter. The double-differenced measurement between a low-Earth-orbiting satellite and international GPS service (IGS) ground stations is constructed to eliminate common errors such as clock errors.

The faculty for using the GPS-based technique with dual frequency to provide precision orbit determination for satellite missions requiring subdecimeter radial orbit accuracy had been verified by the TOPEX/POSEIDON (T/P) satellite.[1,2] In the presence of antispoofing (AS), the T/P orbits processed from GPS single-frequency data are estimated to have a radial orbit accuracy in the range of 4–5 cm rms, and cross- and along-track accuracy of 14-cm rms (Ref. 3). However, because the altitude of the KOMPSAT-2 will

Received 19 October 2001; revision received 18 April 2002; accepted for publication 8 May 2002.

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be lower than the 1336 km of T/P, the unpredictable effects of atmospheric density and mismodeling of the geopotential model will make it difficult to attain comparable orbit accuracy. Moreover, ionospheric calibration using dual-frequency ionosphere free combination is not possible in the case of tracking only the L1 frequency. If ionospheric path delay is not reduced properly, this delay will be the prominent error source together with the cited two effects in low Earth orbit.

Currently, two methods have been implemented to overcome the degradation of the accuracy using the single-frequency GPS data. One is applying the group and phase ionosphere calibration (GRAPHIC) technique[4–6] that averages GPS code pseudorange and carrier-phase observables. This method eliminates the ionospheric path delay using the characteristic of group delay and phase advance due to ionospheric refraction. However, half of the noises of code pseudorange still remains and is a cause for the degradation of accuracy in the process of orbit determination. The other method reduces path delay by using a global ionosphere model.[7] Although this technique has the noise level of the carrier phase, which is 100 times better than that of code, it can not cancel out the path delay completely because total electron content (TEC) values from the ionosphere model have about 30% error.[8] In particular, the unpredictable effects of TEC values can limit accuracy in a low-Earth-orbiting satellite that cruises in the F2 layer of ionosphere. In the past, an experiment with single-frequency GPS data was implemented for the extreme ultraviolet explorer (EUVE) satellite at 500-km altitude. The EUVE process verified that the reduced dynamic parameter estimation using the GRAPHIC method with P1 code and L1 carrier phase could provide 1-m level position accuracy.[9]

To reduce ionospheric path delay in the single-frequency GPS measurements and to determine the position of a low-Earth-orbiting satellite precisely, a new method using only L1 carrier phase is developed in this paper. Because the new method uses the L1 carrier phase, it makes it possible to design a satellite system with the low-cost GPS receiver and to reduce the amount of downlink GPS data. This method is based on a global ionosphere modeling and, in addition, estimates scale factors of TEC values in the locations of the low-Earth-orbiting satellite at each measurement time. The scale factors of TEC values are associated with measurement related parameters in the process of precision orbit determination.

The orbit determination using the real GPS measurements of the T/P and the Challenging minisatellite payload (CHAMP) satellites was conducted to verify the accuracy of the new method. In particular, because the altitude of CHAMP satellite is 460 km, this accuracy will be a reference for the majority of low Earth orbiters. The GRAPHIC technique and the new TEC scale factor estimation method were used to eliminate or reduce ionospheric path delay, respectively. The results of the processes were compared with the precision orbit ephemeris (POE), which was estimated using satellite laser ranging (SLR) and Doppler orbitography and radiopositioning integrated by satellite (DORIS) for the T/P and using dual-frequency GPS data for the CHAMP.

Precision Orbit Determination System

In this research, the precision orbit determination scheme is based on the conventional dynamic parameter estimation that consists of the models of double-differenced GPS measurement between a ground station and low-Earth-orbiting satellite, the precise dynamic models of multispacecraft, and a weighted least-squares batch filter.[10,11] The raw GPS measurements are range data that are computed from measured phase differences between received signals and signals generated by the receiver. These ranges are called pseudorange because they are biased by the GPS satellite and receiver clock errors. Generally, carrier-phase converted pseudorange includes some errors due to the GPS satellite's clock error, receiver's clock error, tropospheric path delay, ionospheric path delay, relativistic effect, data tagging noise, and bias due to integer ambiguity. In the process of precision orbit determination, these errors have to be eliminated by data combination or be corrected by precise measurement models. Explicit double-differenced measurement involves two GPS satellites, one ground station, and a low-Earth-orbiting satellite at the same time. Differencing the GPS data tracked from a low-Earth-orbiting satellite with the GPS data collected from the receivers of IGS ground stations can eliminate the primary measurement errors such as the clock errors of GPS satellites, low-Earth-orbiting satellite, and IGS stations. Explicit double-differenced carrier-phase converted range measurement model can be represented as[10]

$$DD_{iu}^{jk} = \rho_i^j(t_i) - \rho_u^j(t_u) - \rho_i^k(t_i) + \rho_u^k(t_u) - \left\lfloor \dot{\rho}_i^j(t_i) - \dot{\rho}_i^k(t_i) \right\rfloor \cdot \delta t_i + \left\lfloor \dot{\rho}_u^j(t_u) - \dot{\rho}_u^k(t_u) \right\rfloor \cdot \delta t_u + \delta\rho_i^j - \delta\rho_u^j - \delta\rho_i^k + \delta\rho_u^k + C_{iu}^{jk} \tag{1}$$

The GPS measurement models are composed of ionospheric path delay, tropospheric path delay, relativistic effect, phase-center offset and variation of the GPS receiver antenna, and position variation of the ground stations due to the solid Earth tide, ocean loading, and tectonic plate motion. The ionospheric path delay depends on the frequency of the radio signal. Some of this delay can be corrected by using the TEC model.[7,12] If single-frequency measurements are used, this delay can be eliminated by the GRAPHIC technique[9] or be reduced by the TEC scale factor estimation technique that has been developed in this research. Most accurate elimination can be made by ionospheric free combination using dual-frequency GPS data.[13] Modeling troposphere and estimating zenith delay parameters make it possible to correct tropospheric path delay. The carrier phase yields the range between phase center of the receiver and that of the GPS transmitter, but it is biased due to the integer ambiguity. The integer ambiguity, however, is constant over the duration of pass for each specified GPS satellite and receiver pair unless a receiver loses lock on the GPS satellite. A new integer ambiguity is set in the case of losing lock over the duration of pass. The integer ambiguity can be estimated in the process of precision orbit determination.

The precise dynamic models of multisatellites are derived as the equations of motion and variation equations of satellites, and these are integrated numerically in J2000 reference coordinates. The time systems consist of terrestrial dynamic time (TDT), coordinated universal time (UTC), universal time 1 (UT1), and GPS time (GPST). TDT is the base time system in the integration for satellite's equations of motion and variation equations, and it is also used for the coordinate transformation and for the computation of the ephemerides for the sun, moon, and eight planets of the solar system. UTC, which is a timescale based on the definition of the SI second, is used to interpolate the polar motion values, UT1 variation with respect to atomic time international, F10.7-cm solar flux, and 3-h interval K_p Earth magnetic index data from the external files. UT1 is required for computing the Greenwich hour angle, and GPST is applied for GPS measurements time tag. The equations of motion and the variation equations are numerically integrated using Adams–Cowell 11th-order predictor–corrector method (see Refs. 14 and 15). The gravitational forces such as geopotential, the gravity of the sun, moon, and eight planets of the solar system, solid Earth tides, ocean tides, relativistic effect, Earth's dynamic polar motion, and nine parameters empirical general acceleration have to be modeled. The nongravitational forces are composed of atmospheric drag, solar radiation pressure, Earth radiation pressure, and thermal radiation of the satellite. The macromodel,[16] which models the satellite as a combination of flat plates arranged in the shape of a box and the connected solar arrays, is used for the analysis of nongravitational perturbations on a satellite. The attitude mode of the spacecraft is also incorporated.

The epoch state batch filter,[17] where all measurements obtained at different times are mapped to a single epoch to estimate the epoch state, has to be modified to be able to adjust the dynamic parameters, such as coefficients of solar radiation, atmospheric drag, and general acceleration; the measurement biases, such as phase ambiguity and scale factors of TEC value; and the station-related parameters, such as tropospheric zenith delay parameters at user-specified subdivided epochs. The solutions are obtained by applying successive square root free Givens transformation (see Refs. 18 and 19) to the linearized orbit determination problem. Estimating the dynamic related parameters once per specific period has an important role in accounting for deficiencies in the dynamic models. Especially, nine parameters of empirical general acceleration are important to accommodate the errors due to geopotential and atmospheric density mismodeling in low orbit. Empirical general acceleration can be represented, with nine scale factors, as

$$\bar{a}_{ACR} = \begin{bmatrix} \alpha_A \cos u + \beta_A \sin u + \gamma_A \\ \alpha_C \cos u + \beta_C \sin u + \gamma_C \\ \alpha_R \cos u + \beta_R \sin u + \gamma_R \end{bmatrix} \tag{2}$$

Generally, because most of the orbit errors due to mismodeling of gravity and atmospheric drag consist of once and twice per revolution components, α, β, and γ, coefficients are estimated once per orbit period in dynamic orbit determination. However, if measurement errors contaminate the observations to such a degree that the estimation of coefficients is no longer feasible, the coefficients can be estimated once per several minutes interval.

Correction of Ionospheric Path Delay

Because the difference of refractive index between group and phase causes the velocity difference, a group delay and a phase advance occur. In a simplified form, the code delay is a sum of the geometric delay and the delay caused by the ionosphere:

$$\tau_{\text{grp}} = \tau_0 + (40.3 \cdot \text{TEC})/f^2 + \varepsilon_{\text{grp}} \tag{3}$$

The carrier delay can be represented as the geometric delay minus ionospheric delay:

$$\tau_{\text{ph}} = \tau_0 - (40.3 \cdot \text{TEC})/f^2 + \text{bias} + \varepsilon_{\text{ph}} \tag{4}$$

where bias is carrier-phase ambiguity. Because the ionosphere term is identical in both group and phase but appears with opposite sign, averaging these two data types removes the ionospheric term, and the resulting measurement has the type of biased carrier-phase delay with a noise level determined primarily by the much less precise code data:

$$(\tau_{\text{ph}} + \tau_{\text{grp}})/2 \cong \tau_0 + \text{bias}/2 + (\varepsilon_{\text{ph}} + \varepsilon_{\text{grp}})/2 \tag{5}$$

Equation (5) is called the GRAPHIC observables.[4–6] Because the instrument noise of a code observable is greater than that of carrier phase, the GRAPHIC measurement error is a half of code pseudorange noises. This noise can be one of the major causes of accuracy degradation in precision orbit determination.

In the case of using only the carrier phase, the precision of instrument noise is 100 times better than code pseudorange. This is a major merit of using the single-frequency carrier-phase measurement only if the ionospheric path delay can be reduced properly through the modeling of TEC values and the estimation of scale factors of TEC values. The new method for correcting the ionospheric path delay is estimating the scale factors of TEC values ν in the locations of a low-Earth-orbiting satellite once per each measurement time [Eq. (6)]. The double-differenced measurement partial derivative with respect to the scale factor of TEC value can be derived as Eq. (7), and the scale factor is constrained by the a priori covariance in the orbit determination process. The reference TEC values of Eqs. (6) and (7) are also computed by the numerical ionospheric model at each measurement time:

$$\tau_{\text{ph}} = \tau_0 - \frac{\nu \cdot 40.3 \cdot \text{TEC}}{f^2} + \text{bias} + \varepsilon_{\text{ph}} \tag{6}$$

$$\frac{\partial DD_{iu}^{jk}}{\partial \nu} = \frac{40.3 \cdot \text{TEC}_u^j}{f^2} - \frac{40.3 \cdot \text{TEC}_u^k}{f^2} \tag{7}$$

The processes using the two methods, the GRAPHIC method and the TEC scale factor estimation technique, were implemented for eliminating or reducing the ionospheric path delay in single-frequency GPS measurement. The accuracies of two methods were compared with each other.

Results of the Orbit Determination

The dynamic orbit determination using the real GPS measurements of the T/P and the CHAMP satellites was implemented.

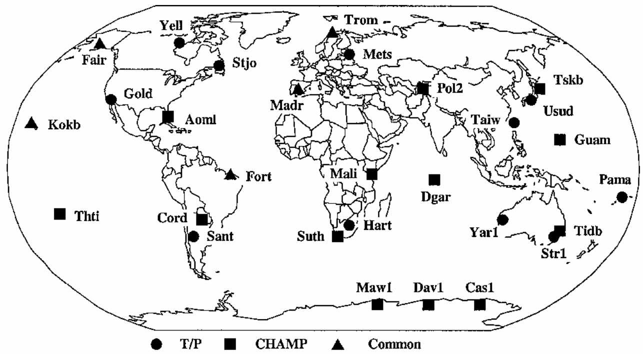

Fig. 1 Ground network of IGS GPS tracking stations: 16 IGS stations used for experiment of T/P and 18 IGS stations for CHAMP.

The dual-frequency carrier-phase data of IGS stations were used to eliminate the ionospheric path delay because IGS station receivers can use cross-correlation techniques to track the L2 carrier phase in the presence of AS. For the low Earth orbiter, both the GRAPHIC technique and the new TEC scale factor estimation method using single-frequency data were applied for ionospheric correction, respectively. GPS measurements from a ground network of several IGS GPS tracking stations (Fig. 1) and a satellite were double differenced. In the estimation process, the joint gravity model 3 70×70 geopotential,[20] extended tidal model, and Mass-Spectrometer-Incoherent-Scatter 86 (MSIS-86) atmospheric density models[21] were applied. The nominal reflectivity, albedo, and emissivity coefficients were used for solar and Earth radiation pressure perturbations, and these values are the same as those used for T/P precision orbit determination process by NASA Goddard Space Flight Center (GSFC). Solar radiation pressure coefficients and atmospheric drag coefficients were estimated once per day. Empirical general acceleration coefficients [Eq. (2)] were also estimated to reduce the errors due to geopotential mismodeling and atmospheric density mismodeling in low orbit. Because the unmodeled and mismodeled forces are resonant at a frequency of once per revolution, it is proper to adjust general acceleration coefficients that have the same frequency. However, because measurement errors due to instrument noise or the mismodeled ionosphere delay contaminate the observations to such a degree that the estimation of coefficients is no longer feasible, the constraint of general acceleration coefficients was set to a quite small value, and the coefficients of periodic and constant terms for along- and cross-track directions were estimated once per 15 min. Station tide corrections approaching the International Earth Rotation Service (IERS) conventions[22] were conducted and No-Net-Rotation (NNR)–Northwestern University Velocity model (NUVEL) 1 (NNR-NUVEL 1) tectonic plate model[23] was used. The Saastamonien model with the Niell mapping function (see Ref. 24) was applied for correcting the tropospheric delay. Tropospheric zenith delay parameters of IGS stations were adjusted once per 2.5 h. The reference ionospheric delay in low Earth orbit was corrected with international reference ionosphere (IRI-95) model,[25] and the scale factors of TEC values [Eq. (6)] were estimated once per each measurement time in the case of the new TEC estimation method. Phase ambiguity biases were also estimated once per each pass. IGS rapid precise orbits of GPS were used without estimating the GPS satellite-related parameters. The parameters estimated in the process are summarized in Table 1.

T/P

The T/P satellite was launched by the Ariane launch vehicle on 10 August 1992. The reference mean elements define a nearly circular frozen orbit with a mean altitude of 1336 km, orbit period of 112 min, and an inclination of 66 deg, which results in a ground track that repeats every 10 days (Ref. 26). The GPS demonstration receiver onboard T/P is a dual-frequency six-channel receiver capable of making continuous carrier-phase measurements at 1-s intervals and P code pseudorange at 10-s intervals.[27] The T/P GPS measurements for 10 days beginning on 13 November 1993 were used in the orbit determination process. The GPS data processing facility of the

Table 1 Parameters estimated in the orbit determination process

Location	Adjusted parameters
Low Earth orbiter	Position and velocity
	Clock offset
	Solar radiation coefficients for once per day
	Atmospheric drag coefficients for once per day
	General acceleration coefficients for once per 15 min
Station	Position and velocity
	Clock offset
	Tropospheric zenith delay parameters for once per 2.5 h
Measurement	Phase ambiguity parameters for each pass
	Scale factors of TEC values for once per each measurement time

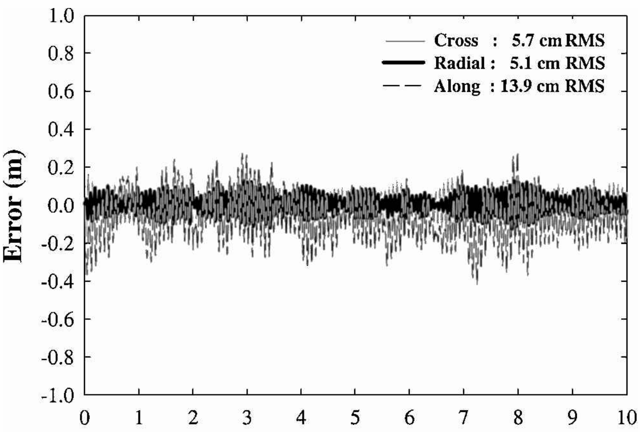

Fig. 2 Results of GRAPHIC technique with L1 carrier phase and P1 code pseudorange for T/P satellite.

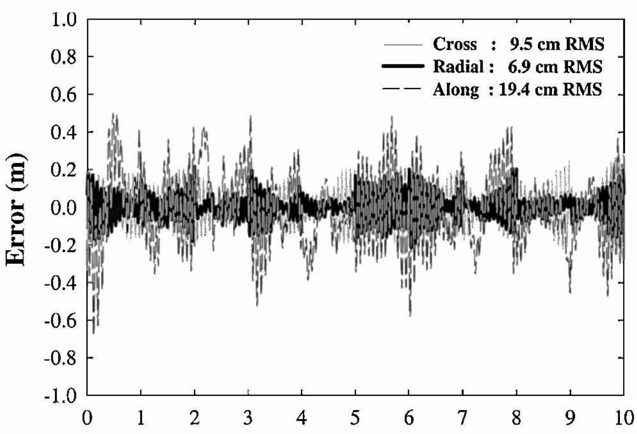

Fig. 3 Results of new TEC estimation method with L1 carrier phase only for T/P satellite.

Jet Propulsion Laboratory (JPL) provided T/P data of L1 and L2 carrier-phase and P code. The L1 and L2 carrier-phase data of 16 IGS stations were used, and double-differenced data were sampled once per 30 s. The data were processed in one day arc. The orbit determination results were compared with T/P POE generated by the Precision Orbit Determination System (PODS) production subsystem at the GSFC, using the global SLR and DORIS measurements.[28]

Figure 2 shows the orbit determination results using the GRAPHIC technique with L1 carrier phase and P1 code pseudorange. The differences from NASA POE are radial 5.1-cm, along-track 13.9-cm, and cross-track 5.7-cm rms. Figure 3 illustrates the results using new TEC value estimation method. The differences from NASA POE are radial 6.9-cm, along-track 19.4-cm, and cross-track 9.5-cm rms. The accuracy of GRAPHIC technique with P1 code pseudorange is slightly better than that of the new TEC value

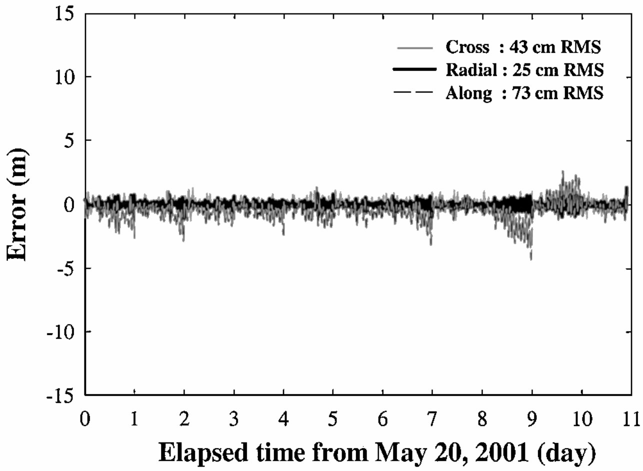

Fig. 4 Results of GRAPHIC technique with L1 carrier phase and C/A code pseudorange for CHAMP satellite.

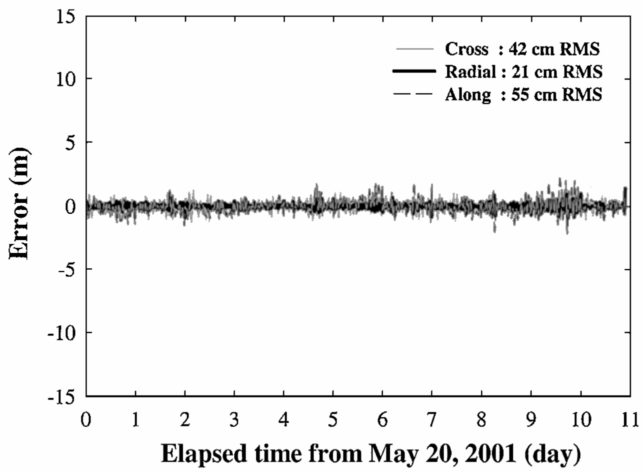

Fig. 5 Results of GRAPHIC technique with L1 carrier phase and P1 code pseudorange for CHAMP satellite.

estimation method with L1 carrier phase only. The new TEC value estimation method can be recommended in the case of AS on or when using the onboard receiver tracking L1 frequency only.

CHAMP

On 15 July 2000, the CHAMP satellite was been launched into a near-polar, circular, low Earth orbit at 460-km altitude. The GPS receiver TurboRogue Space Receiver 2 (TRSR-2) onboard CHAMP was provided by NASA and manufactured at JPL. The receiver acquires a maximum 12 satellites at the same time. From these signals, the orbiting receiver generates at a frequency of 0.1-Hz pseudoranges and carrier phase for all satellites that were in lock at this time instant. The GPS carrier-phase measurements over an 11-day interval, 20–30 May 2001, were used in the orbit determination process. These data were provided by JPL. The L1 and L2 carrier-phase data of 18 IGS stations were used. The double-differenced data sampling is 30 s, as is the the T/P. The orbit determination results were compared with JPL POE that was adjusted using the dual-frequency GPS data and are accurate to about 5 cm in the radial direction and 10–15 cm for three dimensions.[††]

Figure 4 shows the orbit determination results using the GRAPHIC technique with L1 carrier phase and C/A code pseudorange. The differences from JPL POE are radial 25-cm, along-track 73-cm, and cross-track 43-cm rms. Figure 5 shows the results using the GRAPHIC technique with L1 carrier phase and P1 code pseudorange. The differences from POE are radial 21-cm, along-track 55-cm, and cross-track 42-cm rms. Although the GPS

[††]Data available online at URL:http://nng.esoc.esa.de/gps/campaign.html [cited 1 April 2002].

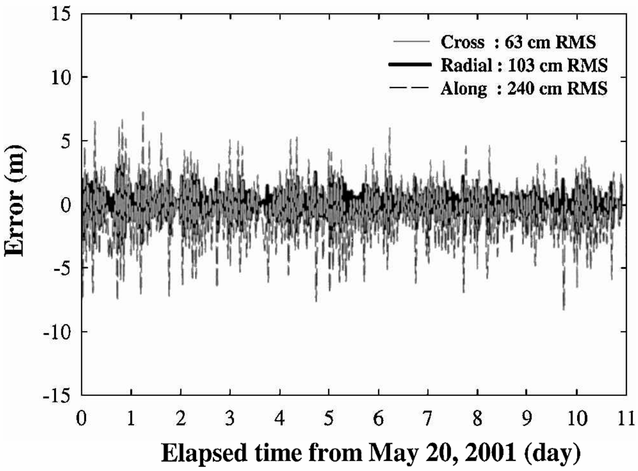

Fig. 6 Results of no TEC estimation method with L1 carrier phase only for CHAMP satellite.

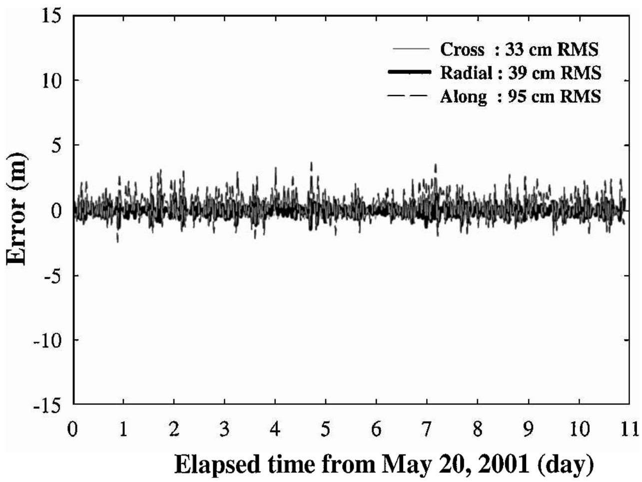

Fig. 7 Results of new TEC estimation method with L1 carrier phase only for CHAMP satellite.

receiver for CHAMP employed an equal noise bandwidth for P and C/A processing, which is called narrow correlator spacing, there are about 24-cm biases in C/A code pseudorange relative to the P1 over the CHAMP campaign period. This bias can be considered as the reason that the C/A GRAPHIC result is somewhat poor in comparison to the P1 GRAPHIC. Below a 500-km altitude, the accuracy of the dynamic parameter determination using the GRAPHIC method with L1 carrier phase and the P1 code pseudorange is similar to that of the reduced dynamic parameter estimation using the same GRAPHIC method, which had been tested on the EUVE satellite.[9] Figure 6 shows the results using L1 carrier phase without the TEC scale factor estimation. The IRI-95 ionospheric model was applied to reference the TEC value. The errors are radial 103-cm, along-track 240-cm, and cross-track 63-cm rms. Although the ionospheric model is used for correcting the ionospheric path delay, the orbit determination accuracy is degraded due to the discrepancy between the true value and the model of TEC. The results using the new TEC value estimation method with L1 carrier phase only are plotted in Fig. 7. The errors are radial 39-cm, along-track 95-cm, and cross-track 33-cm rms. The accuracy of the new TEC value estimation method is a little lower than that of the GRAPHIC method with code pseudorange. However, it shows that the new TEC value estimation method makes it possible to reduce most of the error of ionospheric path delay in the orbit below a 500-km altitude.

Conclusions

The orbit determination system of a low-Earth-orbiting satellite using single-frequency GPS tracking data has been developed. The new TEC scale factor estimation method using L1 carrier phase only was also developed to improve the orbit determination accuracy in low Earth orbit. The precision of the instrument noise of the carrier phase is 100 times better than code pseudorange. The low noise of the carrier phase is a major merit of the new TEC scale factor estimation method if the ionospheric path delay can be reduced properly through the modeling of TEC values and the estimation of scale factors of TEC values. The results of this method were compared with that of the GRAPHIC technique by processing the actual GPS measurements of the T/P and CHAMP satellites. In particular, because the altitude of the CHAMP satellite is 460 km, this accuracy will be a reference for the majority of low Earth orbiters. The orbit determination results verified that, if either the new TEC scale factor estimation method using L1 carrier phase only or the GRAPHIC technique using code were applied, 1-m level position accuracy could be achieved for a low Earth orbiter below 500-km altitude using the GPS-based precision orbit determination. Thus, the new TEC scale factor estimation technique will be the most appropriate method to verify the accuracy and robustness of the GRAPHIC technique in the process of orbit determination for the KOMPSAT-2, which will implement a low-cost and single-frequency onboard GPS receiver generating the C/A code and L1 carrier phase.

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