Adaptive Compensation Method Using the Prediction Algorithm for the Doppler Frequency Shift in the LEO Mobile Satellite Communication System

Moon-Hee You, Seong-Pal Lee, and Youngyearl Han

In low earth orbit (LEO) satellite communication systems, more severe phase distortion due to Doppler shift is frequently detected in the received signal than in cases of geostationary earth orbit (GEO) satellite systems or terrestrial mobile systems. Therefore, an estimation of Doppler shift would be one of the most important factors to enhance performance of LEO satellite communication system. In this paper, a new adaptive Doppler compensation scheme using location information of a user terminal and satellite, as well as a weighting factor for the reduction of prediction error is proposed. The prediction performance of the proposed scheme is simulated in terms of the prediction accuracy and the cumulative density function of the prediction error, with considering the offset variation range of the initial input parameters in LEO satellite system. The simulation results showed that the proposed adaptive compensation algorithm has the better performance accuracy than Ali's method. From the simulation results, it is concluded the adaptive compensation algorithm is the most applicable method that can be applied to LEO satellite systems of a range of altitude between 1,000 km and 2,000 km for the general error tolerance level, M = 250 Hz.

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I. INTRODUCTION

In low earth orbit (LEO) satellite communication systems, more severe phase distortion is frequently detected in the received signal than in case of geo-stationary earth orbit (GEO) satellite systems or terrestrial mobile systems [1]–[3]. Severe phase distortion is from the result of the Doppler frequency shift on the received signal. This distortion comes from the faster movement of a satellite relative to that of a terminal and an earth station. Since the relative velocity of the satellite to the surface of the earth is very fast, the Doppler frequency shift affects the carrier frequencies largely in the communication links. The time variation of the Doppler frequency shift also becomes very large. Its effect on communication links makes the performance of the receiver to be degraded, where the amount of performance degradation depends on the transmission schemes used in the communication systems. Usually, the Doppler frequency shift is more harmful to the digital communication systems employing coherent demodulators. Consequently, there has been much research seeking a method to compensate for the Doppler frequency shift [4]–[7]. Recently, a Doppler estimation scheme using relative time information was introduced [1]. This method pre-compensates for the Doppler frequency shift before carrier recovery.

In [1], a prediction scheme for Doppler frequency shift has been described by using the relative time to the reference time when the satellite makes maximum elevation angle with the user terminal. This algorithm made the prediction equation for Doppler frequency in LEO satellite communication very simple by using the relative time concept. But after the initial parameter setting in this algorithm, the time difference is only a parameter applied to the prediction equation through the time. Therefore, the initial input parameters have a large effect on the prediction error. Due to this error range, the algorithm is limited in application. In order to reduce prediction error, a new prediction method using the information of satellite ephemerides is proposed in this paper.

The cyclic movement of a LEO satellite is represented by deterministic formula with its period. Therefore, if the movement of the terminal is ignored, the Doppler shift, which is in proportion to the relative velocity between a LEO satellite and a terminal, also has its deterministic function, and can be represented in the time domain [8]. Using this in feeder links, the Doppler shift is easily predicted in a fixed earth station because the earth station knows the exact information about its own position and the satellite's time-varing location. But a mobile terminal in user link may not know its own position on time when its power turns on.

In this paper, a new compensation method that is able to estimate a user terminal's position and predict its continuous Doppler frequency shift simultaneously is proposed. First of all, the Doppler frequency shift is described in a closed form with geographical parameters. Next, the Doppler frequency prediction algorithm and the adaptive compensation method using the prediction algorithm by applying the weighting factor are proposed. The performance of this new prediction scheme is compared to that of the known method [1]. In this new prediction method, location information of a user terminal and a satellite is used. Then the prediction performance of the proposed scheme by using LEO satellite constellations has been simulated. The simulation result will demonstrate the enhanced estimation performance of the proposed scheme.

II. DOPPLER SHIFT CHARACTERISTICS IN LEO SATELLITE COMMUNICATION SYSTEM

Doppler shift is a natural phenomenon in mobile communications and causes severe phase distortion and performance degradation especially in LEO mobile satellite communication systems. The Doppler shift characteristics in LEO satellite communication systems is analyzed as follows.

The Doppler frequency shift, $f_D(t)$ is proportional to the carrier frequency f_c. The relative velocity between a transmitter and a receiver, $v(t)$ can be expressed as following (1).

$$f_D(t) = f_c \frac{v(t)}{c}, \tag{1}$$

where c is the velocity of the light.

The relative velocity, $v(t)$, and the distance between a transmitter and a receiver, $s(t)$, can be represented by (2) and (3). Figure 1 shows the geographical configuration between a satellite and a user terminal.

$$v(t) = -\frac{ds(t)}{dt}, \tag{2}$$

$$s(t) = \sqrt{a^2 + r^2 - 2ar\cos\psi(t)}, \tag{3}$$

where a is the radius of the satellite orbit, r is the radius of the earth, and $\psi(t)$ is the separation angle between the satellite and the user terminal as shown in Fig.1.

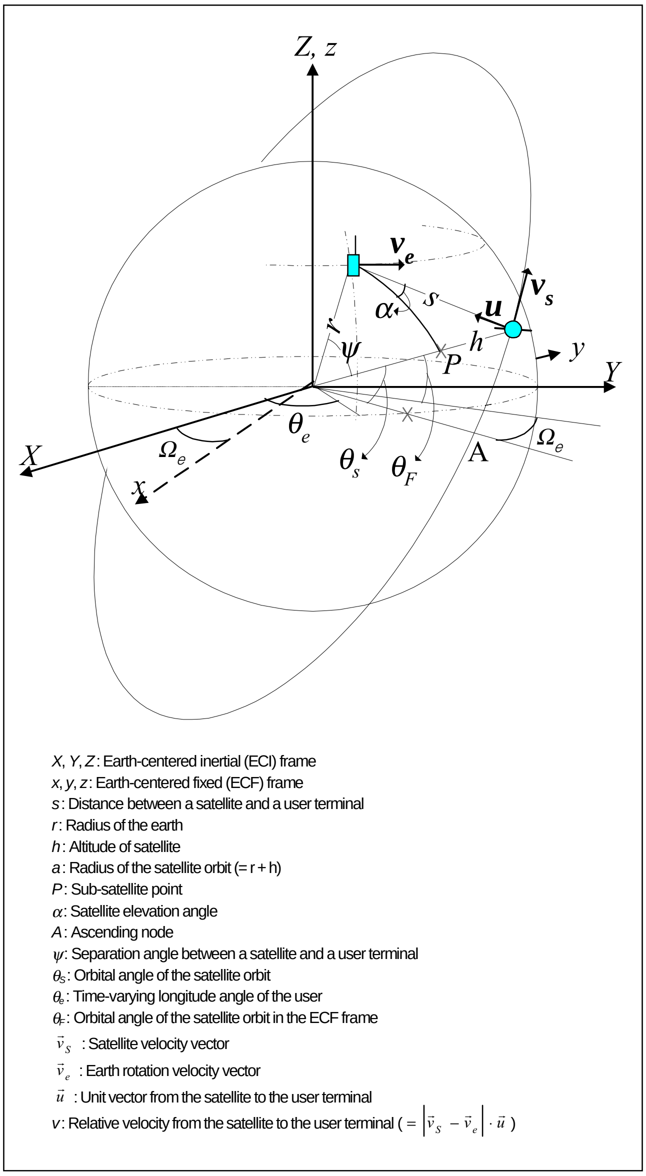

Fig. 1. Geographical configuration of the LEO satellite and the user terminal.

By using (1), (2), and (3), the Doppler frequency shift and its variation rate can be easily derived as shown by (4) and (5).

$$f_D(t) = \frac{f_c}{c}\frac{ar}{s(t)}\frac{d}{dt}\cos\psi(t) \tag{4}$$

$$\dot{f}_D(t) = \frac{d}{dt}f_D(t) = \frac{f_c}{c}\frac{a^2r^2}{s^3(t)}\left(\frac{d}{dt}\cos\psi(t)\right)^2 + \frac{f_c}{c}\frac{ar}{s(t)}\cdot\frac{d^2}{dt^2}\cos\psi(t). \tag{5}$$

When the system parameters, such as, the carrier frequency and the satellite altitude are determined, $\psi(t)$ is an important factor for calculating the Doppler shift frequency.

One of the common methods of expressing $\cos\psi(t)$ can be found in [9], and it is shown in (6). It is characterized in the earth centered inertial coordinate frame by using satellite's orbit angle based on an ascending node, $\theta_S(t)$ and the time-varying longitude angle of the user, $\theta_e(t)$. In this frame, $\theta_S(t)$ and $\theta_e(t)$ can be expressed in terms of the angular velocity of the satellite, ω_s and the angular velocity of the earth, ω_e, respectively.

$$\cos\psi(t) = \cos T_e \cos\theta_s(t)\cos\theta_e(t) + \cos i \cos T_e \sin\theta_s(t)\sin\theta_e(t) + \sin i \sin T_e \sin\theta_s(t), \tag{6}$$

where, i is the orbit inclination angle and T_e is the latitude of the terminal position.

Compared to the classical method, Ali represented $\cos\psi(t)$ as (7) in another approach using the time, t_m at the satellite making maximum elevation angle with the user terminal in the earth centered fixed coordinate frame. In this frame, the angular velocity of the satellite, ω_F varies with latitude due to earth's rotation [1].

$$\cos\psi(t) = \cos(\theta_F(t) - \theta_F(t_m))\cos\psi(t_m), \tag{7}$$

where, $\theta_F(t)$ is the orbital angle of the satellite on the basis of the satellite ascending node in the earth centered fixed coordination $(= \omega_F \cdot t + \theta_F(0))$.

In this paper, $\cos\psi(t)$ is represented as equation (8) using the user terminal's position, *i.e.*, the latitude, T_e and the longitude, G_e, which are practically more applicable parameters than $\theta_s(t)$, $\theta_e(t)$ or $\psi(t_m)$, $\theta(t_m)$ in the earth centered fixed coordinate frame.

$$\cos\psi(t) = \cos T_s(t)\cos T_e \cos(G_s(t) - G_e) + \sin T_s(t)\sin T_e \tag{8}$$

where T_s and G_s are the latitude and the longitude of the satellite position, respectively. It is assumed that the user terminal can easily obtain this information of satellite ephemerides at time t.

Actually, many satellites such as Globalstar [10] and KOMPSAT [11], [12] have the onboard GPS receivers. In Globalstar system, the mobile user terminals can determine which particular satellite should be in view and get the knowledge of satellite ephemerides.

After obtaining the function of $\cos\psi(t)$ from one of the above equations, the Doppler frequency shift can be calculated by using (4). If the calculated value of $\cos\psi(t)$ is more accurate, the prediction accuracy of the Doppler frequency shift is higher. Now the adaptive compensation method is presented using the new prediction algorithm for the Doppler frequency shift by using (8).

III. ADAPTIVE COMPENSATION METHOD

Now, it is very clear that selection of a certain expression for $\psi(t)$ would determine the required parameters for Doppler calculation and that the prediction of the instantaneous Doppler frequency would be able to compensate the exact Doppler frequency.

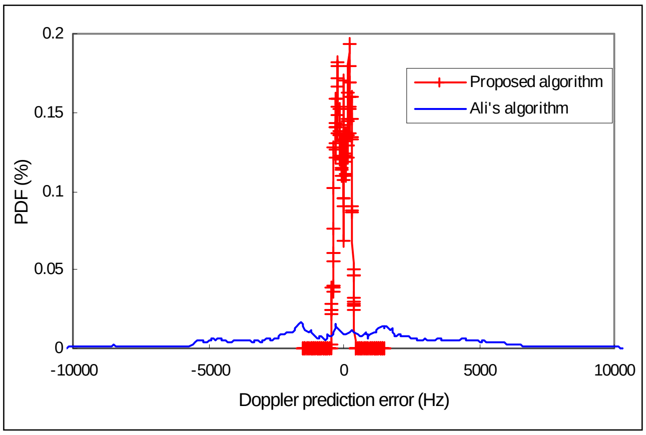

Fig. 2. Probability density function of the prediction error of the doppler frequency.

As mentioned above, a prediction scheme for Doppler frequency shift by using an expression for $\psi(t)$ represented as (7) has been described in [1] by Irfan Ali, where the estimation of the Doppler frequency is based on the relative time to the reference time when the satellite makes maximum elevation angle with the user terminal. This algorithm made the prediction equation for Doppler frequency in LEO satellite communication very simple by using the relative time concept. But after the initial parameter setting in this algorithm, the time difference is only a parameter applied to the prediction equation through the time. Therefore, the initial input parameters have a large effect on the prediction error. The performance of Ali's prediction algorithm is presented on Fig. 2 showing the probability density function of the Doppler frequency prediction error. This result is obtained under the condition that the LEO satellite is at the altitude of 780 km as shown in Fig. 2. The prediction algorithm proposed in [1] produces a Doppler frequency estimation with a large variance of prediction error. Due to this error range, the algorithm is limited in application.

In this paper, to get a better performance, new compensation method is suggested as follows. In proposed scheme, key parameters determining new prediction algorithm for the Doppler frequency shift are the latitude and longitude information of the user terminal's position. In order to get the user terminal's position information, the distance function, $s(t)$, between satellite and user terminal has to be found.

1. The Algorithm Determining Distance between Satellite and User terminal, $s(t)$

In order to get the distance, $s(t)$, between satellite and user terminal, an equation of the second degree of $s(t)$ could be made by using (3), (4), and (5). Then, to simplify the second derivative of $\cos\psi(t)$ in (5) and to replace it with the function of $s(t)$, we introduce the approximation function of the angular velocity of the satellite in the earth centered fixed coordinate frame, ω_F. The equatorial component of ω_F is dependent on the latitude of the sub-satellite point due to earth's rotation. For LEO satellites, we can minimize the effect of the latitude of the sub-satellite point on the angular velocity of the satellite and replace the term of the latitude of the sub-satellite point to the term of the orbit inclination angle. Therefore, the angular velocity of the satellite, ω_F can be approximated by the following equation.

$$\dot{\theta}_F(t)=\frac{d}{dt}\theta_F(t)=\omega_F(t)\approx\omega_s-\omega_e\cos i \tag{9}$$

Applying (7) and (9), we obtain the approximation of the second derivative of $\cos\psi(t)$ as (10).

$$\frac{d^2}{dt^2}\cos\psi(t)\approx-\omega_F^2\cdot\cos\psi(t) \tag{10}$$

Now, by using (4) and (10) into (5), the following (11) of second degree of $s(t)$ can be expressed in the closed form. By selecting the geographically correct solution between two roots of the quadratic (11), the distance $s(t)$ can be obtained.

$$s^2(t)-\frac{2c\dot{f}_D(t)}{\omega^2 f_c}s(t)-\left[\left(a^2+r^2\right)-2\left(\frac{cf_D(t)}{\omega f_c}\right)^2\right]=0. \tag{11}$$

2. The Algorithm Determining the Terminal Position, T_e and G_e

We select the results, $s(t_1)$ and $s(t_2)$, by using the measured Doppler frequency shifts, $f_D(t_1)$ and $f_D(t_2)$, and Doppler shift rates, $\dot{f}_D(t_1)$ and $\dot{f}_D(t_2)$ at sampling instants, t_1 and $t_2(>t_1)$, respectively. As applying distances $s(t_1)$ and $s(t_2)$ into (3), $\cos\psi(t_1)$ and $\cos\psi(t_2)$ can be obtained. By applying $\cos\psi(t_1)$ and $\cos\psi(t_2)$ into (8), the simultaneous equations for two parameters, the latitude, T_e and the longitude, G_e of the terminal position can be obtained. By applying trigonometric function, the terminal position information is obtained as shown in (12) through (14). The lower subscripts, 1 and 2 shown in these equations indicate the sampling instants, t_1 and t_2, respectively.

$$\sin G_e=\frac{(A_2D_1-A_1D_2)-(A_2C_1-A_1C_2)\sin T_e}{(A_2B_1-A_1B_2)\cos T_e} \tag{12}$$

$$\cos G_e=\frac{(B_2D_1-B_1D_2)-(B_2C_1-B_1C_2)\sin T_e}{(A_1B_2-A_2B_1)\cos T_e} \tag{13}$$

$$\sin T_e=\frac{k_2\pm\sqrt{k_2^2-k_1k_3}}{k_1} \tag{14}$$

where,

$$A_n=\cos T_s(t_n)\cos G_s(t_n),\quad B_n=\cos T_s(t_n)\sin G_s(t_n)$$
$$C_n=\sin T_s(t_n),\quad D_n=\cos\psi(t_n)$$
$$k_1=(A_2C_1-A_1C_2)^2+(B_2C_1-B_1C_2)^2+(A_1B_2-A_2B_1)^2$$
$$k_2=(A_2C_1-A_1C_2)(A_2D_1-A_1D_2)+(B_2C_1-B_1C_2)(B_2D_1-B_1D_2)$$
$$k_3=(A_2D_1-A_1D_2)^2+(B_2D_1-B_1D_2)^2-(A_1B_2-A_2B_1)^2$$

3. Compensation Method Using the Doppler Frequency Prediction Algorithm

Now, the Doppler frequency shift could be predicted by using the terminal position parameters, because those parameters have been estimated. A new prediction equation of the Doppler frequency shift, $f_{DM1}(t)$ can be obtained as by (15). The system could continuously perform the compensation operation against the phase distortion due to Doppler shift by using the Doppler prediction values.

$$f_{DM1}(t)=arf_c\left\{\left[\left[-\omega_s\sin i\cos\left[\sin^{-1}\left(\frac{\sin T_s(t)}{\sin i}\right)\right]\right]\tan T_s(t)\cos(G_s(t)-G_e)\right.\right.$$
$$\left.\left.-\left(\frac{\omega_s\cos i}{\cos T_s(t)}-\omega_e\cos T_s(t)\right)\sin(G_s(t)-G_e)\right]\cos T_e+(\omega_s\sin i\cos\theta_s(t))\sin T_e\right\}$$
$$\Big/\left[c\sqrt{a^2+r^2-2ar(\cos T_s(t)\cos T_e\cos(G_s(t)-G_e)+\sin T_s(t)\sin T_e)}\right] \tag{15}$$

Figure 3 shows the exact Doppler frequency shift, $f_D(t)$ and the predicted frequency shift, $f_{DM1}(t)$ under the condition that the carrier frequency is 2.4 GHz and given different altitudes of the satellite. In Fig. 3, it is shown that the predicted frequency shift, $f_{DM1}(t)$ follows the exact Doppler frequency shift, $f_D(t)$ very well, and Fig. 2 shows that the prediction performance of the new prediction algorithm is better than that of the algorithm in [1] by means of the comparison between the variances of the prediction errors for these two prediction algorithms.

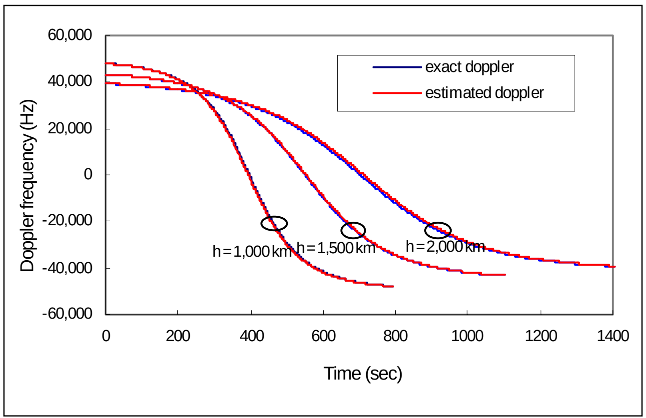

Fig. 3. Comparison between the exact Doppler frequency shift, $f_D(t)$ and the predicted frequency shift, $f_{DM1}(t)$ at f_c=2.4 GHz.

Considering the system operation, the prediction error tolerance is very important not only for statistical reasons but also in the instantaneous time aspect. Let the instantaneous error, $e(t)$ be defined as the difference between the exact Doppler frequency, $f_D(t)$ and the predicted frequency shift, $f_{DM1}(t)$, and the upper limit of the error equal *M,* as the error tolerance level which is generally adopted as about 250 Hz in real systems .

$$e(t) = f_D(t) - f_{DM1}(t) \le M \tag{16}$$

Figure 4 shows the instantaneous error, $e(t)$, of the predicted Doppler frequency, $f_{DM1}(t)$ in the cases of different altitudes of satellite, in which the exact initial Doppler frequencies, $f_D(t_1)$ and $f_D(t_2)$ were used for the input parameters. By observing Fig.4, one can notice two facts, the one is that the prediction errors are not tolerable during most of the period, and the other is that the instantaneous error seems to be dependent on the distance, *s*, the separation angle, ψ, or the satellite elevation angle, α. In fact, this error is caused by the approximated angular velocity of the satellite, ω_F in (9).

4. Adaptive Prediction Algorithm of the Doppler Frequency Shift with the Weighting Factor

To minimize the error in $f_{DM1}(t)$, the prediction algorithm

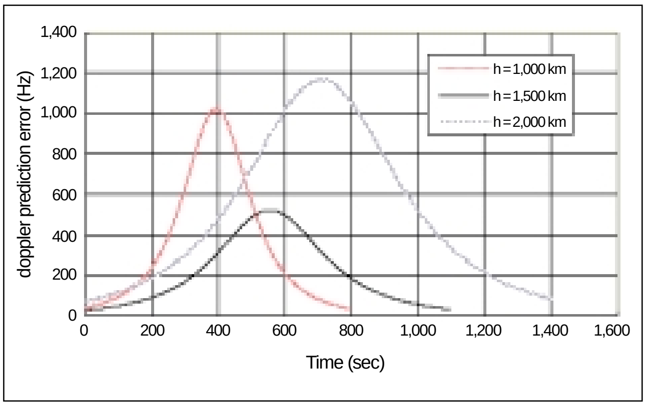

Fig. 4. Instantaneous error of the new prediction algorithm.

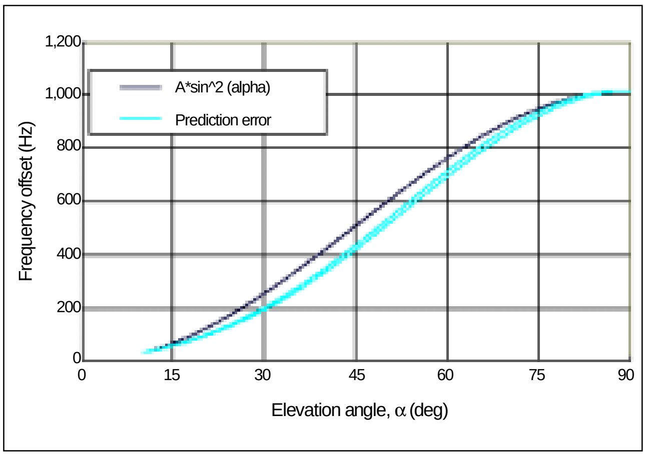

Fig. 5. Prediction error of doppler frequency shift versus the satellite elevation angle.

could be considered to the adaptive scheme by introducing the weighting factor, W.

As shown on Fig. 5, the prediction algorithm of the Doppler frequency shift, $f_{DM1}(t)$, has error especially around the maximum elevation angle, and the trend of the instantaneous prediction error follows sin-square function of the elevation angle. To reduce the errors at higher elevation angles, a new adaptive prediction algorithm is suggested as follows.

According to the approximation of the instantaneous error function mentioned above, the weighting factor, $W(t)$ is introduced by the following equation. In the process of the Doppler frequency prediction, the satellite elevation angle is estimated by using (18). Therefore, the instantaneous weighting factor, $W(t)$ is obtained very easily.

$$W(t) = A_h \cdot \sin^2 \alpha(t), \tag{17}$$

$$\sin \alpha(t) = \frac{a^2 - r^2 - s^2(t)}{2rs(t)}, \tag{18}$$

where, A_h is the normalizing factor depending on latitude of the satellite. The comparison between the prediction error in (16) and the weighting factor in (17) is shown in Fig. 6. In (19), by adding the weighting factor, $W(t)$ to the estimated Doppler frequency, $f_{DM1}(t)$, the adaptive Doppler frequency prediction, $f_{DM2}(t)$ comes closer to the exact Doppler frequency.

$$f_{DM2}(t) = f_{DM1}(t) + W(t). \tag{19}$$

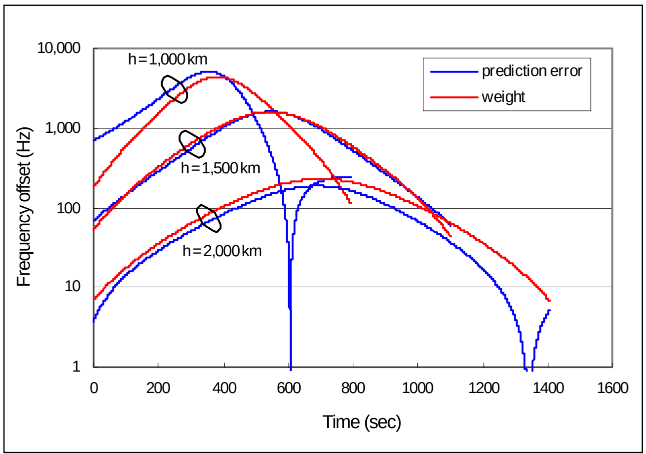

Fig. 6. Comparison between the prediction error and the weighting factor.

IV. SIMULATION RESULT

The performance of the two proposed prediction scheme is simulated, one without the weighting factor and the other with the weighting factor. Then, the simulation results are compared to those of Ali's scheme. The LEO satellite system is assumed to be one of two types, one with a circular orbit of altitude 1000km or the other of altitude 2,000 km. Each satellite orbit is assumed to be inclined by 52º. It is assumed that a user terminal is located on the equator for the worst case, and the initial input Doppler frequency offset varies in the range of up to 500 Hz from the exact Doppler frequency for the practical situation.

In Fig. 7, we show the results of the prediction error by simulation. We compare the accuracy of the performance between the prediction algorithms, in terms of the coefficient of determination factor, R^2 defined as following (20). This coefficient of determination factor represents the normalized accuracy.

$$R^2 = \frac{\sum(f_D - \bar{f}_D)^2 - \sum(f_D - f_{DM})^2}{\sum(f_D - \bar{f}_D)^2} \tag{20}$$

where, f_D is the exact Doppler frequency, $\bar{f}_D$ is the average of f_D, and f_{DM} is the predicted Doppler frequency by using one of three Doppler prediction algorithms mentioned above, *i.e.*, proposed prediction algorithm without weighting factor, proposed adaptive compensation algorithm with weighting factor and Ali's prediction algorithm.

As shown in Fig. 7, the adaptive compensation algorithm using the weighting factor improves performance accuracy better than Ali's algorithm and the suggested compensation algorithm with no weighting factor.

For example, in the case of LEO satellite of altitude 1,000 km, if the accuracy of the prediction is required to be 99.5 %, then the adaptive compensation algorithm tolerates the offset variation of the initial measured Doppler frequency up to 260 Hz. But under the same condition, the prediction algorithm with no weighting factor permits the offset variation up to 105 Hz, and Al's prediction algorithm permits the offset variation up to 90 Hz.

In the case of LEO satellite of altitude 2,000 km, the adaptive compensation algorithm with weighting factor provides nearly perfect prediction accuracy considering the initial frequency offset variation of up to 500 Hz.

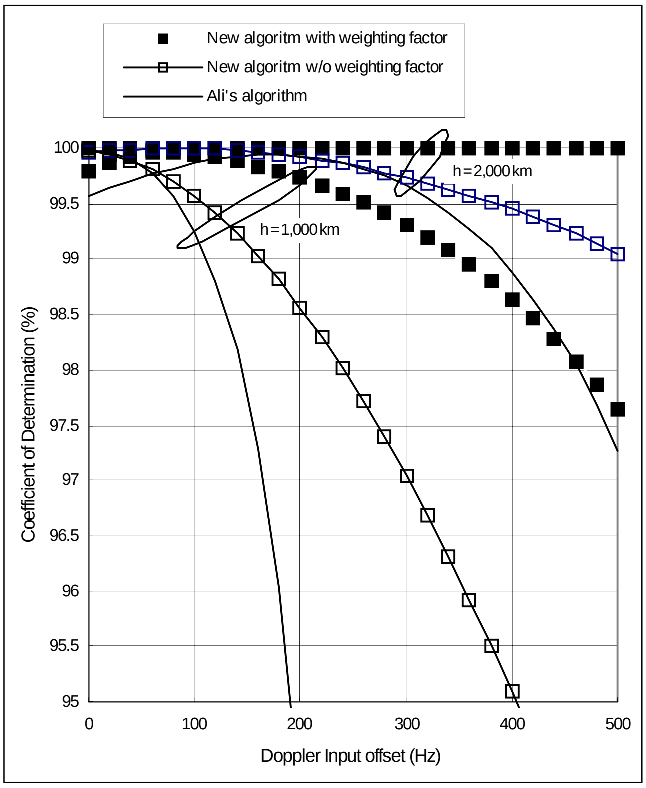

Fig. 7. Prediction accuracy comparison depending on doppler input offset.

Figure 8 shows the cumulative distribution function of the prediction error for each Doppler frequency prediction algorithm. In the case of LEO satellite of altitude 1,000 km, the adaptive compensation algorithm meets the prediction error requirement which is generally related with the error tolerance level, for example 250 Hz in typical GMPCS systems. However, other algorithms can not satisfy this error requirement. As for the proposed prediction algorithm without weighting factor, the probability is 17 % in case of the prediction error to be less than 250 Hz. As for Ali's prediction algorithm, the probability is only 0.7 % in the same case. This means that in case of the prediction error to be more than 250 Hz the probability is 99.3 % by using Ali's prediction algorithm.

In the case of the adaptive compensation algorithm with weighting factor in the satellite of altitude 2,000 km, possibly occurred prediction error is less than 50 Hz. In Fig. 8 with conclusion, the adaptive compensation algorithm the most applicable method to be applied in the LEO satellite system of altitude from 1,000 km to 2,000 km for the general error tolerance level, $M = 250$ Hz.

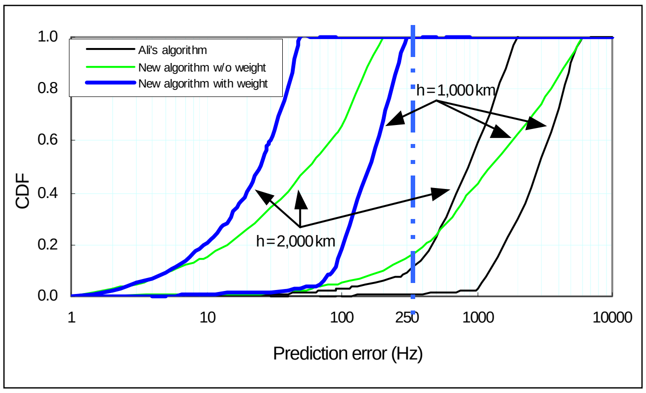

Fig. 8. Cumulative distribution function of the prediction error.

V. CONCLUSION

In this paper, we have proposed a Doppler prediction algorithm based on the information of the instantaneous satellite position and the estimated terminal position for LEO satellite systems. In addition, new adaptive compensation algorithm for Doppler frequency shift was suggested from this Doppler prediction algorithm with the weighting factor for the reduction of prediction error.

For the performance evaluation, the prediction accuracy and the cumulative density function of the prediction error for the proposed algorithms were simulated and the results were compared to those of Ali's Doppler prediction scheme. For the practical simulation results, we considered the offset variation range of the initially measured Doppler frequency input and the error tolerance level.

From the simulation results, the proposed adaptive compensation algorithm with weighting factor provides nearly perfect prediction accuracy considering the initial frequency offset variation of up to 500 Hz in case of LEO satellite of altitude 2,000 km. And the adaptive compensation algorithm is the most applicable method to be applied in the LEO satellite system of altitude from 1,000 km to 2,000 km for the general error tolerance level, M = 250 Hz. The simulation results show that our proposed adaptive algorithm is better than Ali's algorithms. Although the proposed scheme needs a little bit more calculation loads, the Doppler prediction error range that has to be covered by frequency synchronization circuit is much smaller. Therefore, this proposed algorithm makes frequency acquisition and tracking step simple.

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