SINGLE FREQUENCY REFRACTION CORRECTION

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1. Abstract

In satellite navigation systems the ionospheric effects can be measured indirectly knowing the dispersion laws in the ionosphere. Most satellite navigation systems are performing the same measurements on two different carrier frequencies, while a combination of modulation and carrier measurements is used less frequently. A combination of Doppler measurements on both the carrier and the modulation is known under the acronym DRVID.

Both navigation systems GPS (USA) and GLONASS (Soviet Union) only make available one out of two transmission frequencies to civilian users. On the other hand, the DRVID method requires very long integration times. A new method is proposed here, using a combination of time-delay (ranging) measurements on the modulation and Doppler-shift measurements on the carrier. According to the given quantities (carrier frequency and modulation bandwidth of available satellite navigation systems) the proposed method allows the correction of the ionospheric errors up to the accuracy allowed by other error sources of the satellite navigation system and at the same time, the proposed method does not require a longer measurement integration time. The proposed method requires a suitable ionospheric model. An additional drawback is the requirement that the user velocity has to be accurately known.

To check the proposed method a suitable GPS receiver was developed. Practical measurement results show that the ionospheric-effect related error can be reduced by a factor between 5 and 10 times, the residual error being equal or smaller than other error sources. The receiver design and the measurement results are also shown.

2. Introduction

The operation of all radio-navigation systems is based on the fact that the propagation time of a radio signal can be measured easily with simple equipment. The system accuracy depends on the accuracy to which the propagation speed of radio waves is known. The accuracy of all satellite navigation systems is limited by the ionosphere. The propagation speed in the ionosphere is different from that in free space and is time dependent. Besides periodic daily, yearly and 11-year sunspot-cycle variations the ionosphere may change in a random fashion too.

Ionospheric effects can be measured indirectly knowing the dispersion laws in the ionosphere. At L-band frequencies the only significant effect is a small increase of the phase velocity of the radio-wave and a small decrease of the group velocity of the modulation. Both effects are of equal magnitude but opposite signs and are inversely proportional to the square of the frequency (see Fig. 1). As long as these effects are small, the actual distribution of the charged particles along the whole radio-path is unimportant for the final result, the only important quantity being the total number of charged particles in a tube of unit cross-section along the radio-path.

$$V_f = c \cdot \left(1 + \frac{Q^2 N}{2 m \varepsilon_0 \omega^2}\right)$$

$$V_g = c \cdot \left(1 - \frac{Q^2 N}{2 m \varepsilon_0 \omega^2}\right)$$

$c \equiv$ free-space light speed
$Q \equiv$ particle charge
$N \equiv$ particle density
$m \equiv$ particle mass
$\varepsilon_0 \equiv$ free-space dielectric constant
$\omega \equiv$ frequency
$V_f \equiv$ phase velocity
$V_g \equiv$ group velocity

Fig.1 - Group and phase velocity in the ionosphere.

Most satellite navigation systems are performing the same measurements on two different carrier frequencies since the absolute error can be derived easily from the difference between the two results. The two measurements can be performed on the modulation delay or Doppler shift: in this case the ionosphere is increasing the propagation delay. In the case of carrier Doppler measurements, the effect is opposite: the ionosphere is decreasing the propagation delay.

A combination of modulation and carrier measurements is used less frequently: because of dispersion the ionospheric effect on the modulation has the opposite sign when compared with the same effect on the carrier. A combination of Doppler measurements on both the carrier and the modulation is called DRVID (Differentiated Range Versus Integrated Doppler). This method has the advantage that a single carrier frequency is required. The main drawback is that in practical satellite navigation systems only Doppler measurements can be performed on the carrier. Considering the ratio between the carrier frequency and modulation bandwidth, the corresponding Doppler measurements on the modulation are very noisy and therefore require very long integration times for the same measurement accuracy.

Finally, it is also possible to use ionospheric data obtained from other sources to correct the errors caused by ionospheric effects. In the case of navigation satellites, the satellite navigation data format usually also includes information about the current ionosphere in the form of parameters for a published ionospheric model. Since the actual ionosphere may differ from the model used and the received data may be several hours old, this method is considered far less accurate.

3. Single-Frequency Ionospheric Refraction Correction

A single-frequency ionospheric refraction correction method is interesting since both navigation systems, GPS (USA) and GLONASS (Soviet Union) only make available one out of two transmission carrier frequencies to civilian users. Unfortunately, the DRVID method requires very long integration times for the required accuracy.

A new method is proposed here, using a combination of time-delay (ranging) measurements on the modulation and Doppler-shift measurements on the carrier frequency.

Time-delay (ranging) measurements on the modulation are the most common way to use GPS. A typical user (who does not have access to a highly-accurate local time reference) receives signals from four satellites and computes his tri-dimensional coordinates from modulation time differences. The user may also compute accurate time at his location as additional data. The ionosphere adds a variable delay to the modulation of the satellite signal. With a given ionosphere, this delay depends mainly on the elevation of the satellite above the horizon. The delay is the smallest for a satellite at zenith, since the propagation path through the ionosphere is the shortest and it is the largest for a satellite just above horizon, since the radio-wave path through the ionosphere is much longer. The ionosphere thus behaves as a diffusing (concave) lens for the satellite signal modulation. The ionosphere will therefore cause the largest error in the measured user altitude, which will result higher than real. Errors in the measured longitude and latitude will be smaller.

Carrier Doppler-shift measurements were mainly used with earlier satellite navigation systems. With GPS, carrier-doppler shift measurements are generally used to find the user velocity. If the user velocity is accurately known (both magnitude and direction), then the tri-dimensional position can be computed from carrier Doppler-shift measurements. Since a typical user does not have access to a highly-accurate local frequency reference, four satellite signals are required just like in the case of time-delay (ranging) measurements. The ionosphere increases the phase velocity of the radio-waves, therefore its effect on carrier measurements is exactly opposite: the ionosphere behaves as a concentrating (convex) lens. The largest error will be again in the measured user altitude, which will result lower than real. Errors in the measured longitude and latitude will be smaller.

The combination of both results obtained from time-delay (ranging) measurements on the modulation and Doppler-shift measurements on the signal carrier is however not straightforward. Although the Doppler navigation equations are just time derivatives of the time-delay (ranging) navigation equations, the solutions are quite different if both equation sets are solved for the user position. Therefore, the corrected user position is not a simple mean of the two results although the ionospheric effects on the modulation and on the carrier are exactly opposite.

In time-delay (ranging) measurements, the ionosphere adds four additional unknowns: the ionospheric delays for the four satellites required for navigation. In Doppler-shift measurements, the ionosphere adds another four unknowns: the rates-of-change of the ionosphere in the directions of movement of the four satellites required for navigation, raising the total number of ionosphere related unknowns to eight. On the other hand, the proposed method only provides four equations at best, related to the three measured user coordinates and to the comparison between measured user time and frequency. The latter equation requires a long frequency integration time and can not be considered useful, so the problem has three usable equations to be solved for eight unknowns.

Since there are more unknowns than equations, the proposed method can not accurately correct all possible errors induced by the ionosphere. Fortunately, the real ionosphere, although unpredictable, appears only at certain altitudes with a well-known vertical profile and only changes slowly with longitude and latitude. The ionospheric errors can be thus corrected by adopting a model for the ionosphere which includes a certain number of carefully chosen parameters. The latter are found by solving the available equations.

The most straightforward ionospheric model has three parameters: a constant concentration and two linear variation rates along longitude and latitude. In this case, the number of unknowns is equal to the number of available equations. An even simpler model considers the ionosphere invariable along longitude and latitude, the only parameter being a constant concentration. In this case a single equation is required: considering that the largest error occurs in the measured user altitude, it makes sense to use the equation that results from both measured altitudes (modulation delay and carrier Doppler).

Since the proposed method for ionospheric refraction correction includes several assumptions, some practical experiments had to be performed to establish whether it is really useful with an existing satellite navigation system (GPS) or not. First, the accuracy of available GPS signals is not specified for Doppler navigation. Second, the effects of multi-path propagation on the navigation accuracy when using Doppler measurements on GPS signals were not known either. Finally, provided that a suitable navigation receiver hardware is made available, different ionospheric models should be tested. From all of the above it is clear that a test receiver had to be built and practical measurements had to be performed to test the viability of the proposed method.

4. Receiver Design

Although GPS C/A code only receivers are readily available, it was decided to build a special receiver for the purpose of testing the proposed method of ionospheric refraction correction. This was necessary since the constructional details, especially the operating software, and some critical specifications, like the ability of accurately measuring carrier-Doppler shifts, are usually not available from the manufacturers.

The block diagram of the receiver is shown on Fig.2. The receiver includes an analog RF front-end and two analog IF channels, while the computer is only used for data processing. All measurements are performed exclusively in a differential way, using as the reference the signal from one of the two satellites received at the same time, to avoid any error sources related to the receiver electronics. Further, the measurement resolution of both time and frequency measurements was selected between one and two orders of magnitude better than what required to perform the measurements.

Of course, a two channel receiver has to scan among the

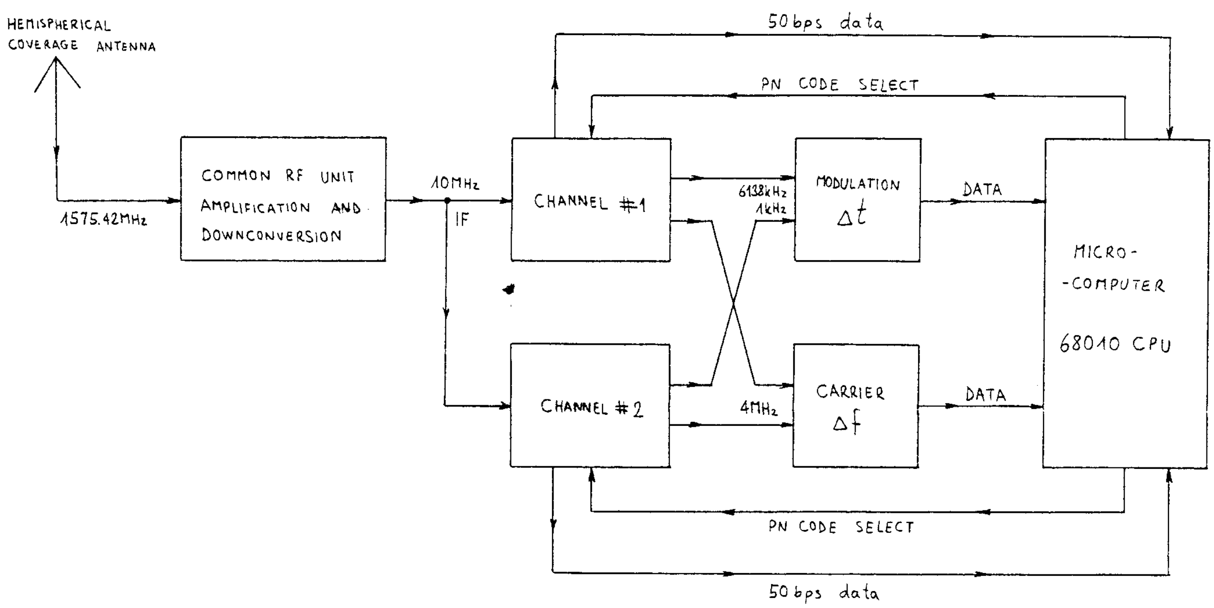

Fig.2 - Two-channel GPS receiver.

four satellites required for tri-dimensional navigation. Since the analog electronics requires several seconds to lock on another satellite signal, the receiver was designed to track one pair of satellites for about one minute and then switch to another pair of satellites. Since instantaneous differential measurements are only performed to cancel-out any errors introduced by the local time/frequency reference oscillator, the navigation solution can only be found after three such cycles.

The receiver software includes both tri-dimensional navigation solutions for time-delay and Doppler equations with tropospheric refraction corrections and extensive error-checking procedures to remove any bad data from the final result. Finally, the proposed ionospheric refraction correction is applied. Due to the slow scanning among different satellites, this receiver is only suitable for stationary user measurements, but this is considered enough to prove the feasibility of the proposed method.

5. Measurement Results

Before trying the proposed method for ionospheric refraction correction, the receiver hardware and software had to be accurately tested. One also had to find out whether GPS signals were accurate enough (satellite transmitter phase noise and/or propagation effects) for Doppler navigation. Although commercial GPS receivers use the carrier Doppler to compute the user velocity, the accuracy required for the proposed method is between two and three orders of magnitude higher.

In order to check the overall system accuracy, night-time measurements were performed first. At night, the ionospheric effects on GPS signals are at least an order of magnitude smaller than during daylight. In the case of a C/A only GPS receiver, at night the ionospheric effects are smaller than other error sources. Two typical night-time plots, taken just after local midnight, are shown on Fig.3 and Fig.4. The quantity observed is the altitude above seal level, since it is the most affected by the ionosphere. The vertical scale on the plots extends from 0 to 245 meters, the true altitude of the receiving antenna being around 120m. The horizontal axis is the time scale: the starting point, number of data points and duration in minutes are indicated in the annotation line.

The plots on Fig.3. and 4. include both results: the altitude obtained from modulation time-delay measurements (thick line) and the altitude obtained from carrier Doppler measurements. It can be easily noted that both navigation methods provide the same result at night and that the Doppler result is just slightly noisier than the time-delay result. Considering the time scale, the noise is mainly due to multi-path propagation, since the antenna was installed close to other metal structures and without any anti-reflection ground-planes.

On the other hand, day-time measurements show a notable difference of 50 to 70 meters between the altitude obtained from modulation delay measurements (thick line) and carrier Doppler measurements (thin line). Both plots on Fig.5 and Fig.6 were taken around local noon, when the illumination of the ionosphere was at maximum. Although the true altitude lies in between the two measured values, the corrected altitude is not a simple arithmetic mean of the two: some vector algebra is still required to obtain the corrected altitude, longitude and latitude.

Finally, the results using the proposed ionospheric refraction correction method are shown on Fig.7 and Fig.8. The two thin lines on these two figures are obtained from the the same code-delay and Doppler-shift measurements as on Fig.5 and Fig.6 while the thick line shows the corrected altitude above sea level. The straight line corresponds to the the true altitude of the receiving antenna (120m), obtained as an average of night-time measurements while the altitude scale ranges from 0m to 245m like on all previous plots.

A very simple ionospheric model was used for the corrections on Fig.7 and Fig.8 representing an ionosphere with constant thickness and electron concentration. The latter was adjusted so that both modulation delay and carrier Doppler measurements resulted in the same computed user altitude. Additional care was taken by the software when either navigation equation system determinant (delay or Doppler) was ill-behaved or when the final correction method equation system was poorly defined.

As a conclusion, the results of the measurements show that the proposed method for single-frequency ionospheric refraction correction can reduce the related error by a factor between 5 and 10, making it comparable or smaller than other system error sources, even with a simple model for the ionosphere.

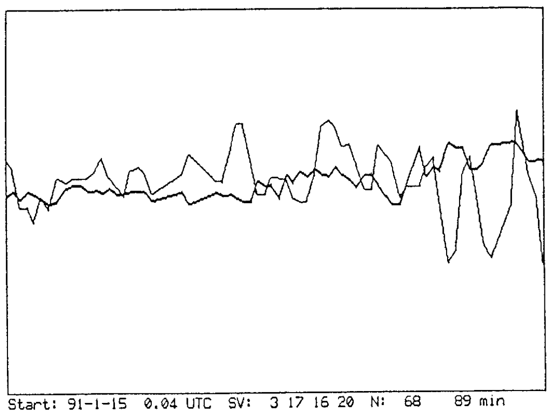

Fig.3 - Night-time measurement.

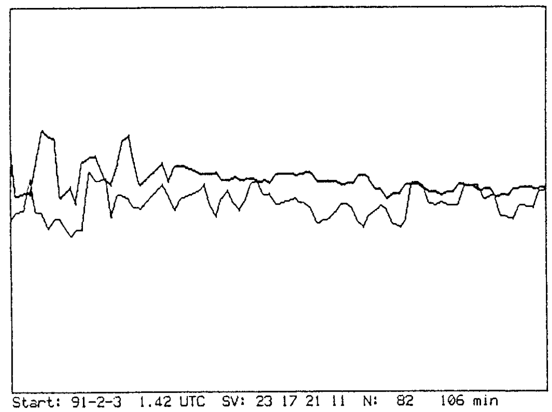

Fig.4 - Night-time measurement.

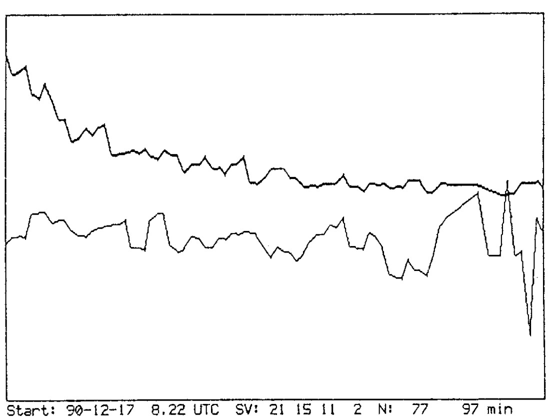

Fig.5 - Daylight measurement.

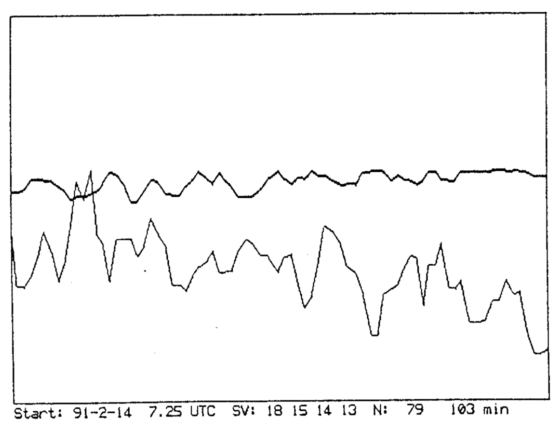

Fig.6 - Daylight measurement.

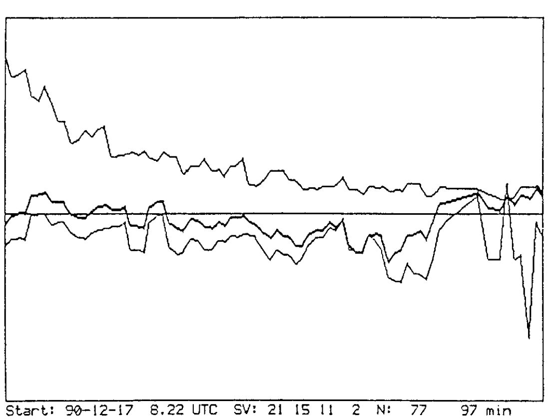

Fig.7 - Daylight measurement with correction.

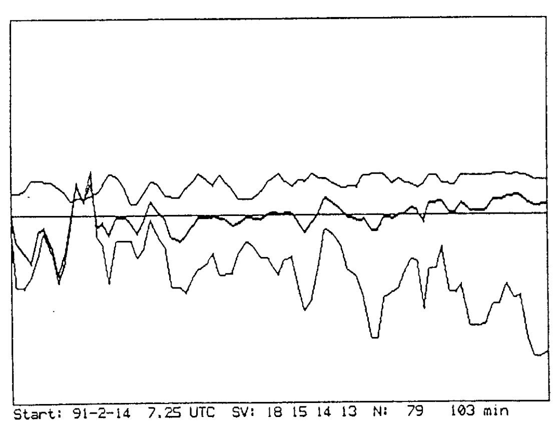

Fig.8 - Daylight measurement with correction.