INDEX

Long-Baseline (>400 KM) On The Fly Ambiguity Resolution
Using Ionospheric Corrections with High Geomagnetic Activity.

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ABSTRACT

A procedure for resolving carrier phase ambiguities, even under unfavorable geomagnetic conditions, has been tested. Precise ionospheric corrections have been made using dual-frequency data from control stations. Successful results will be presented, based on data collected during a period of high geomagnetic activity from an area straddling the North West of the United States and the South West of Canada. The corrections have been obtained modelling the ionosphere by computed tomography. This technique could enable wide area GNSS networks to support sub-decimeter differential surveying and navigation in real time.

BIOGRAPHIES

Dr. Oscar L. Colombo works on applications of space geodesy, including gravity field mapping, spacecraft orbit determination, and precise positioning by space techniques. In recent years, he has developed and tested techniques for very long baseline kinematic GPS.

Dr. Manuel Hernández-Pajares is associate professor in the Department of Applied Mathematics and Telematics at the Universitat Politècnica de Catalunya. He started working on GPS in 1989 and now he is currently focused on the area of GPS Ionospheric tomography, neural network algorithms and precise radionavigation.

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INTRODUCTION

The free electrons distributed in the ionosphere (between one hundred and thousands km in height) produce a frequency-dependent effect on the Global Positioning System (GPS) signals: a delay in the pseudorange and an advance in the carrier phase. Their spatial-temporal distribution is correlated with the position of the main source of ionization: the Sun. It is also dependent on the solar cycle, on events such as travelling ionospheric disturbances (TID) and, in general, on geomagnetic and "space weather" conditions.

Therefore, the distribution of free electrons in the ionosphere affects precise navigation with GPS, and must be taken into account depending on the distance scale.

The dual frequency GPS signals, gathered from a set of reference receivers, can be used to compute a real-time ionospheric model for regional and wide-area differential GPS augmentations (RADGPS, WADGPS) This model can be used to make precise ionospheric corrections for navigation. Some examples can be found in [1] for WADGPS, using as the main observable the smoothed pseudorange for meter-level positioning, and in [2] for RADGPS, close to the Solar maximum and using the carrier phases for sub-decimeter level positioning.

REAL-TIME TOMOGRAPHIC MODEL

The free electron density can be described as a random walk process in time that can best be estimated in a Sun fixed reference frame where it is relatively stationary (variation of ±5% during one day with low geomagnetic activity). The tomographic model adopted is spatially formed by a set of cells or volume elements (voxels), especially suitable to detect local features, that cover all the ionosphere sampled by the GPS satellites/receivers rays. In these voxels the electron density is considered uniform at any given time. Voxels of 3x5 degrees in latitude and solar longitude, forming two layers with boundaries at 60-740-1420 km, have been adopted (see figure 1). This resolution is adequate to get precise ionospheric estimates from ground GPS data (e.g., [3]).

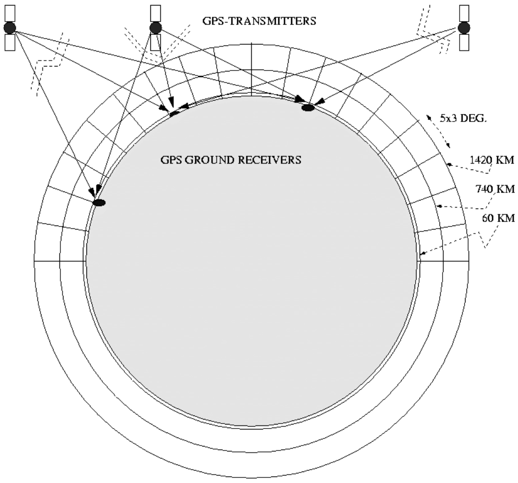

Figure 1. Layout of the tomographic model of the ionosphere

The parameters of the model are estimated with a Kalman filter. Thie filter uses as data the geometry-free combination of phases, L_I, of the transmitter T measured from receiver R: $L_I=L_1-L_2=SUM_{ijk}\ (N_e)_{i,j,k}\ \Delta s_{i,j,k} + b$ being L_1 and L_2 the carrier phases (in meters) at frequencies $f_1=154\ f_0$ and $f_2=120\ f_0$ ($f_0=10.23$ MHz); where i,j,k are the indices for each cell corresponding to solar longitude, geodetic latitude and height; $(N_e)_{i,j,k}$ is the free electron density; and $\Delta s_{i,j,k}$ is the length of the ray path crossing the "illuminated cells"; and b is the alignment term (constant in a given transmitter-receiver arch of continuous phase) that includes the L_1, L_2 integer ambiguities and instrumental delays. This approach extends the model described in [4] by Hernández-Pajares et al., to real-time applications. For further details, see also [5] and [6].

RESOLVING THE AMBIGUITIES IN REAL TIME FOR THE REFERENCE SITES

(a) Resolving the wide lane

If we consider the wide lane combination for the reference stations $L_\delta=(f_1 \cdot L_1-f_2 \cdot L_2)/(f_1-f_2)$, then the double difference between a satellite and the reference satellite (D), and then a station and reference station (Δ), can be written as

$$D\Delta L_\delta = D\Delta\rho + D\Delta T + D\Delta I_\delta + \lambda_\delta\ D\Delta N_\delta \qquad (1)$$

Where: ρ the distance satellite-receiver, T the tropospheric delay, I_δ the wide lane ionospheric correction and N_δ the integer wide lane ambiguity (centimetric terms like the phase multipath have been neglected).

To fix in real time $D\Delta N_\delta$ to the right integer value from equation (1), it is necessary to find the other three terms with a maximum total error less than $\lambda_\delta/2=43$ cm, i.e. with an error standard deviation less than 21.5 cm, to guarantee the 95% of successful determination, assuming the error is normally distributed. An error of few centimeters can be expected for the satellite-receiver distance term DΔρ, when using precise ephemeris. If the broadcast ephemeris are used instead, this error term is typically less than 10 cm at distances of 500 km, and can be made negligible if the orbit error is estimated in real-time using the stations GPS data [7]. Regarding the double-differenced tropospheric correction $D\Delta T$ for stations at distances of few tens of km, the maximum error using the models for the hydrostatic and wet components is typically lower than 10 cm for elevations greater than 20 degrees (this corresponds to a worst case in the study by Coster et al.[8], figure 5d). But this error can diminish to a few centimeters if the tropospheric refraction is estimated in real time, in particular at reference stations with coordinates known at the cm-level. In our case, using precise orbits and modeled tropospheric corrections, a standard deviation of the error of 20 cm in ΔI_δ should result in a successful resolution of. ΔN_δ 95% of the time.

(b) Resolving the L1 and L2 ambiguities

Once ΔN_δ is fixed, it becomes posible to fix the L_1 and L_2 double-differenced integer ambiguities, N_1 and N_2 at the reference stations, by using an accurate enough determination of the double-differenced bias ΔB_c of the ionospheric-free combination L_c,

$L_c=(f_1^2\ L_1 - f_2^2\ L_2)/(f_1^2-f_2^2)$.

The following relationships illustrate these steps:

$$D\Delta B_c = 0.5[\lambda_\delta\ D\Delta N_\delta + \lambda_n\ D\Delta(N_1+N_2)]\ , \qquad (2)$$

$$D\Delta(N_1+N_2) = NI[(2D\Delta B_c - \lambda_\delta\ D\Delta N_\delta)/\lambda_v]\ , \qquad (3)$$

$$D\Delta N_1 = 0.5[D\Delta N_\delta + D\Delta(N_1+N_2)]\ , \qquad (4)$$

and, finally,

$$D\Delta N_2 = D\Delta N_1 - D\Delta N_\delta \qquad (5)$$

being $\lambda_n=c/(f_1+f_2)=10.7$ cm, and NI the nearest integer. Hence, from $D\Delta N_1$ and $D\Delta N_2$, the unambiguous double-differenced ionospheric Slant Total Electron Content (STEC) can be computed for the reference stations: $D\Delta STEC = D\Delta(L_1 - L_2) -(\lambda_1\ D\Delta N_1 - \lambda_2\ D\Delta N_2)$. Finally, and following the procedure described in [2], one can try to solve the carrier phase ambiguities for a roving receiver , correcting them with the unambiguous double-differenced ionospheric STEC interpolated from the reference stations to the rover.

RESOLVING AMBIGUITIES ON THE FLY FOR THE ROVER

(a) Resolving the wide lane

The double-differenced wide lane is first corrected for the ionosphere using the modeled STEC interpolated to the rover. Then the ionosphere-free combination Lc is subtracted from the corrected wide lane. Finally, an estimate of the Lc bias is subtracted as well. This is repeated for every double difference for which there might be a reliable ionospheric correction (satellites above 25 degrees in elevation).

The result is a noisy estimate of the wide lane ambiguity (in meters), with an error that is a combination of the carrier phase noise, the error in the ionospheric correction, and the error in the estimated Lc bias.

The wide lane ambiguity can be found by rounding off each of these estimates to the nearest integer number of wide lane wavelengths. Errors in computed tropospheric refraction, reference station coordinates, and satellite ephemeris, cancel out when subtracting Lc from the wide lane. Assuming the ionospheric correction is sufficiently accurate to resolve the L1 and L2 ambiguities (< 2.7 cm error in *LI*), the main uncertainty is that in the Lc bias. Assuming, further, that the main sources of uncertainty are normally distributed, then the error in the Lc bias should be less than 1/4 of a wide lane (< 21.5 cm) for the procedure to work well at least 95% of the time.

The Lc bias must be estimated simultaneously with the position of the rover, which, in general, cannot be considered sufficiently well known beforehand.

As for the fixed sites, the other unknowns are the errors in the tropospheric zenith-delay correction and in the GPS ephemeris. A Kalman filter is used to obtain a joint solution for the present position and all the other unknowns (in post-processing one would use first a filter, then a smoother).

This joint kinematic solution has been obtained with software developed by the first author for precise, long-range kinematic and static positioning [9], [10], modified to use the ionosphere corrections. The calculation also yields the precision of each estimated Lc bias, to decide when this estimate is precise enough to use safely.

(b) Resolving the L1 and L2 ambiguities

Once the wide lane integer ambiguity is known, one can proceed to determine the L1 and L2 phase ambiguities as in the previous section, expressions (1 - 5).

Having found those ambiguities, the exact Lc bias can be calculated and assimilated in the Kalman filter, as a pseudo-observation. Some "noise" uncertainty must be assigned to each pseudo-observation. A noise a priori sigma of 3 cm was chosen by trial and error.

The procedure outlined above does not require an integer search, as long as the various uncertainties are smaller than the specified bounds. Moreover, the effect of data noise has been reduced using averaged data. This has been easy to do, because this long-range procedure uses data compression (averaging) to economize CPU time and hard-disk space. It takes between two and six consecutive updates of the filter, with 2-minute carrier phase averages, to get Lc bias estimates with a precision of 20 cm or better and resolve the wide lane.

No ambiguity is considered resolved unless the absolute value of the residual *LI,* after correcting and removing the estimated ambiguity, is less than 1.5 cm. No resolved Lc biases are accepted unless they pass a null-hypothesis error test before being assimilated in the Kalman filter. And, while many Lc biases might be satisfactorily resolved every two minutes, only those biases poorly known (worse than 3 cm-precision) are updated with their resolved values. Integer ambiguities may be resolved many times during a run, but their resolved values will be used only if necessary.

TEST IN THE PACIFIC NORTHWEST

The data set came from five North-American reference stations belonging to the International GPS Service (IGS). It was collected on May 3rd,1999, between 20 and 23 hours UTC. That was a period of high ionospheric activity (Kp=6). The baselines ranged from 400 to 1000 km in length. The observations were dual-frequency carrier-phase and pseudorange, collected at the typical IGS rate of 30 seconds. Data sets from four stations (CABL, GWEN, HOLB, WILL), were used to create the ionospheric model. Data from all five sites (those mentioned, plus ALBH, near Victoria) were used in the tests described below, and are shown on a map in Figure 2. While all data had been collected beforehand, we took care to process them as they would be in real-time.

RESULTS

Checking the ionospheric corrections against the known STEC at ALBH

The rms of the discrepancy between the interpolated, double-differenced STEC correction and its known value, for the baseline HOLB (the "base station") to ALBH (the "rover"), is much less than one half-cycle of the widelane. So it is accurate enough to resolve the widelane ambiguities between HOLB and ALBH.

The ALBH data have been reserved for testing. The L1, L2 ambiguities of the carrier phase, double-differenced relative to HOLB, are to be resolved on the fly, as part of a kinematic solution in which the station is treated as the "rover" (with HOLB as base station).

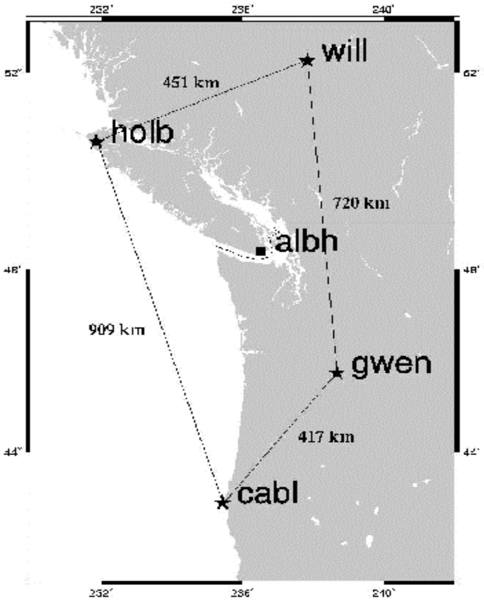

Figure 2. IGS sites used in the Pacific Northwest test.

As expected, more than the 90% of successful wide lane fixing is obtained for elevations greater than 20 degrees (100% without the satellite PRN10) in contrast to the minimum elevation of 50 degrees when the double difference ionospheric correction is neglected (figure 3).
By interpolating the unambiguous DΔ*STEC* values of the reference stations, it is posible to solve the full set of ambiguities, when this value is more accurate than 2.7 cm.

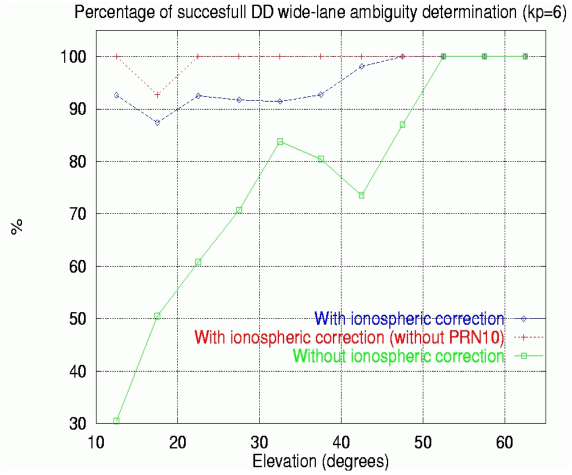

Figure 3. Percentage of succesful wide lane integer ambiguity determination at the reference stations as a function of the lowest satellite elevation.

Resolving the L1 and L2 ambiguities on the fly for the "Rover" (ALBH)

The instantaneous position of ALBH relative to HOLB, 420 km away and on the opposite end of Vancouver Island, was calculated kinematically and then compared to the known position of ALBH. Solutions were made using: (a) precise IGS ephemeris (from SP3 orbit files); (b) broacast ephemeris (from the navigation message). In both cases the L1 and L2 ambiguities were found on the fly, as discussed in previous sections. The actual position of ALBH was known with centimeter-level precision from an independent IGS solution, after taking into account the solid-earth tidal displacement. This was not used to help the kinematic solutions, but was used to test their accuracy. When using the broadcast ephemeris, as in a true real-time case, their errors were estimated, along with residual zenith delays, floated Lc biases, and the position of the vehicle.
The a priori uncertainties for the vehicle were σ = 100 m per coordinate. The uncertainties in those coordinates were asigned zero-memory, or white noise, error states. So no dynamics were assumed for the vehicle (kinematic solution).

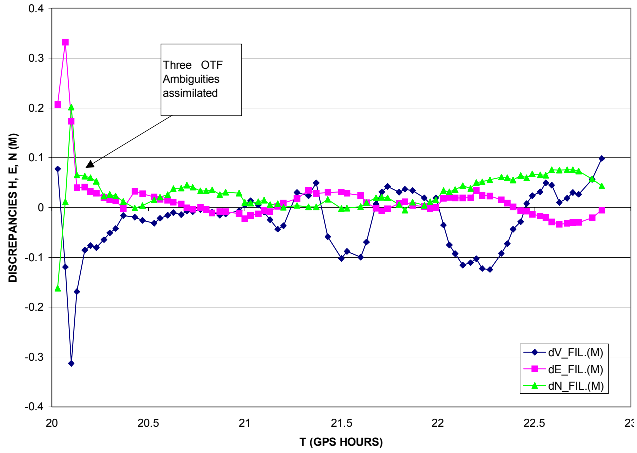

Figure 4. Vertical, East, and North discrepancies (in meters) between ALBH kinematicly determined position relative to HOLB , 420 km away, and its precise static position. Broadcast orbits used (and simultaneously adjusted) as in real time.

Each on-the-fly solution has been tested in two ways:

(a) Observing the discrepancies between the known and the kinematic determined position of ALBH. Since the resolved ambiguities were used solely when needed, this first test only covers attempts to resolve ambiguities obtained soon after gaining, or regaining, lock. The resulting Vertical, East, and North discrepancies are shown in figures 4 and 5. At the start of the run, it takes ten minutes, while also correcting the broadcast orbits, for three double differences to be fully resolved and all three position discrepancies to fall below 10 cm. That time comes down to eight minutes when using the (fixed) SP3 orbits. With the broadcast orbits there are two small excursions outside the +/-10 cm bounds, later in the run. This happens when the orbit errors of several newly risen satellites begin to be estimated with a priori uncertainties of 2 m per coordinate. There are no signs of incorrectly resolved ambiguities, such as clearly discernible linear trends in the discrepancies. When using the SP3 orbits (not adjusted), the Lc biases converged very fast.

(b) Comparing the Lc biases Bc calculated from the resolved N1 and N2 integers (whether used or not) to their precise post-processed estimates Bc^*. These were obtained while fixing the well-known positions of ALBH and HOLB, and the precise SP3 orbits from the IGS.

The L1, L2 ambiguities can be regarded as successfully resolved if for the Lc bias is $|Bc-Bc^*| < 2$ cm.

There were a total of 180 attempts to resolve the ambiguities in the 3-hour period (for all double differences with satellites above 25^o). Criteria (b) was satisfied 71% of the time with both the broadcast and the SP3 orbits. The possible errors did not appear to exceed +/- 1 cycle in both L1 and L2 (the wide lane was always correctly resolved). The error in the Lc biases was +/- 11 cm, at most. This error was taken into account, giving a conservative standard deviation of 6 cm to the resolved biases.

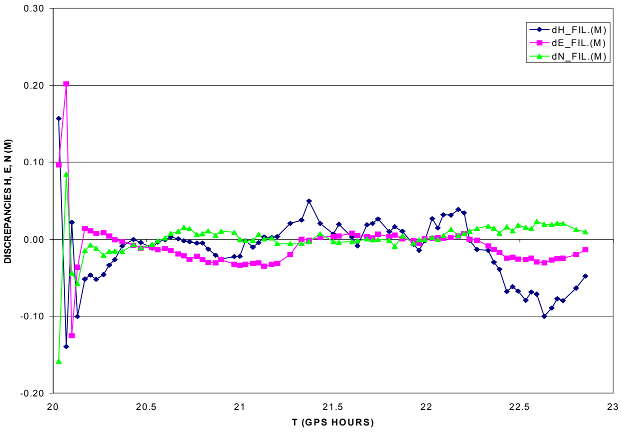

Figure 5. Same as in Figure 4, but using precise SP3 orbits (from the IGS) instead of the broadcast ephemerides. The SP3 orbits were not adjusted in this run. Accuracy reaches 10 cm in eight minutes.

CONCLUSIONS

The tomographic modelling of the ionosphere, implemented in real time with dual-frequency receiver data, can be precise enough for the successful resolution on the fly of the wide lane and STEC ambiguities, even with high geomagnetic activity (Kp=6), and with distances of many hundreds of kilometers between receivers.

Inside an area surrounded by a few GPS reference sites, the estimated unambiguous STEC can be interpolated with sufficient accuracy to the location of a roving receiver. The results of the test shown here suggests that better than 10 cm accuracy can be achieved within 10 minutes of starting the Kalman filter, and that this accuracy can be maintained most of the time thereafter.

All calculations needed to implement and test the techniques described here were made in ordinary personal computers.

ACKNOWLEDGMENTS

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