Feasibility of Wide-Area Subdecimeter Navigation With GALILEO and Modernized GPS

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***Abstract*—Precise corrections with a three-dimensional voxel model of the ionosphere based on global navigation satellite system (GNSS) data from a wide-area network of ground receivers can help resolve differential carrier-phase ambiguities over very long baselines of hundreds of kilometers in present two-frequency systems [global positioning system (GPS) and global orbiting navigation satellite system (GLONASS)] or in planned three-frequency systems (GALILEO, Modernized GPS). A study based on simulated three-frequency data from a modified GNSS signal generator indicates that all the phase ambiguities could be resolved successfully more than 90% of the time. This should be useful in surveying large areas with instruments that require very precise geolocation (e.g., radar or Lidar altimetry, interferometric synthetic aperture radar, interferometric sonar, etc.)**

***Index Terms*—Ambiguity resolution, carrier-phase, differential global positioning system (DGPS), GALILEO, global navigation satellite system (GNSS), kinematic global positioning system, navigation, wide area.**

I. Introduction

Notation

- c speed of light;
- f is frequency;
- λ wave-length;
- s carrier-phase;
- p pseudorange;
- ρ distance;
- I proportional to the total electron content along the signal path;
- I/f_i^2 ionospheric group delay;
- N ambiguity in whole cycles;
- e measurement noise;
- m signal multipath.

IN WHAT FOLLOWS, all phase and pseudorange observations are understood to be used in the form of double differences, i.e.,

$$s = (s^{jk} - s^{jK}) - (s^{Jk} - s^{JK})$$

where s^{nm} is the observation from satellite n at receiver m, and the uppercase indicates the reference satellite and receiver. The frequencies are f_1, f_2, and f_3, each with corresponding phase and pseudorange s_1, s_2, s_3, and p_1, p_2, p_3. Moreover

$$\lambda_\iota s_i = \rho + \lambda_\iota N_i - \frac{I}{f_i^2} + e_{s,i} + m_{s,i}$$
$$p_i = \rho + \frac{I}{f_i^2} + m_{p,i} + e_{p,i}, \qquad i = 1, 2, 3.$$

The observed slant total electron content (STEC) is

$$\text{STEC} = \frac{I}{f_2^2} - \frac{I}{f_1^2} = \lambda_1 (s_1 - N_1) - \lambda_2 (s_2 - N_2).$$

The ionosphere-free phase combination L_c is

$$L_c = a \cdot s_1 + b \cdot s_2$$

where

$$a = \frac{cf_1}{(f_1^2 - f_2^2)} \quad b = -\frac{cf_2}{(f_1^2 - f_2^2)}.$$

L_c has an offset or bias $B_c = aN_1 + bN_2$. The *extra-widelane* and *widelane* phase combinations are $s_{\text{ew}} = s_1 - s_2$, and $s_{\text{w}} = s_1 - s_3$. Their wavelengths are

$$\lambda_{\text{ew}} = \frac{c}{(f_1 - f_3)} \quad \lambda_{\text{w}} = \frac{c}{(f_1 - f_2)}.$$

The pseudorange narrowlane combination is

$$p_{\text{narr}} = \frac{c}{(f_1 + f_3)} \left[\frac{f_1}{c} p_1 + \frac{f_3}{c} p_3 \right].$$

Note: The extra-widelane and the pseudorange narrowlane have the same ionospheric delay.

General: Long-range, real-time, carrier-phase, kinematic differential global positioning systems (DGPS), with subdecimeter three-dimensional (3-D) precision and separations of up to several hundreds of kilometers between the roving receiver and the nearest reference station, is an enabling technology for large-area remote sensing surveys requiring very precise sensor geolocation. To achieve high precision quickly requires the resolution of the carrier-phase ambiguities. Ambiguity resolution methods work well as long as the difference in ionospheric signal delay between receivers is negligible, e.g., when they are near each other. With the usual real-time kinematic (RTK) approach, subdecimeter precision can be achieved very quickly, as soon as the ambiguities are resolved. But the ionosphere usually limits this to distances of less than 20 km.

Other undesirable effects on the signals will cancel out between nearby receivers, but will be quite significant over long baselines. Among those effects are broadcast orbit errors, tropospheric refraction correction errors, and floated

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ionospheric-free combination (L_c) biases. These are nuisance unknowns that have to be estimated in the navigation Kalman filter along with the position of the vehicle. The navigation filter typically assimilates phase and pseudorange observations from several receivers every second; it is fully updated once a minute and estimates 50–100 active error states. To determine position accurately, the filter first has to converge, assimilating enough GPS data to estimate all unknowns precisely. This could take the better part of an hour. The main reason for this delay is the estimation of the floated L_c biases. If one could resolve the corresponding ambiguities, by using accurate ionospheric corrections, and then use the result to eliminate the biases, convergence would be much faster, and precise navigation could begin at once [1], [2].

Several techniques have been proposed to resolve ambiguities over short baselines for future global navigation satellite system (GNSS) systems with three L-band frequencies ($\mathrm{L}_1, \mathrm{L}_2, \mathrm{L}_3$), such as Galileo and the Modernized GPS. These include three-carrier ambiguity resolution (TCAR) [3], Integrated TCAR (ITCAR) [4], and Cascade Integer Resolution (CIR) [5]. These share a similar basic approach. The double-differenced integer ambiguities are successively solved from the longest to the shortest beat-wavelength: first the “extra-widelane” and next the “widelane” (with wavelengths of about 5.9 and 0.86 m, respectively, in the case of Modernized GPS), and finally the L1 carrier (19 cm). The main advantage is that this can be done in a geometric-free way, and then at single epoch (instantaneous) mode.

Both TCAR and ITCAR are adversely affected by ionospheric refraction decorrelation at distances greater than 10–20 km. The ionosphere delay becomes a problem when its differential value is greater than 0.26 total electron content units (TECUs) ($1\ \mathrm{TECU} = 10^{16}$ electrons/m^2) $\approx$ 16 cm in L1. This also corresponds to 4 cm in L1, or one half-cycle of the ambiguous ionospheric slant TEC (STEC), as computed from the difference between the L1 and L2 signals, after resolving the wide-lane ambiguity, so N1-N2 is already known.

The new technique presented here extends to three-frequency systems, previous work by the authors on two-frequency ambiguity resolution with ionospheric corrections. These corrections can be generated in real time from a tomographic description of the ionosphere obtained with a dedicated Kalman filter, using dual-frequency carrier-phase data from a network of reference ground stations. This technique is called wide-area real-time kinematic (WARTK) [6], [7].

II. Technique

A. TCAR

This method consists of three basic steps.

Step 1) Solve the extra-wide lane ambiguity, or N_{ew}, with a synthetic wavelength of $\sim$ 7.45 m (in our simulated dataset) by subtracting the pseudorange narrowlane and then rounding off the difference to the nearest whole number of wavelengths

$$N_{\mathrm{ew}} = \mathrm{Nint}\left\{\lambda_{\mathrm{ew}}\left(s_1 - s_3\right) - p_{\mathrm{narr}}\right\}$$

where “Nint” means *“rounded off to the nearest integer.”*

Subtracting N_{ew} from s_{ew} gives the unambiguous value of the phase wide lane. Although in some cases excessive pseudorange multipath can diminish the chances for success, this error is typically small compared with the long wavelength of the extra-wide lane.

Step 2) The wide lane combination ambiguity N_{w} is estimated by subtracting from the ambiguous wide lane the unambiguous extra-wide lane obtained in Step 1, and rounding off the result to the nearest number of whole cycles of the widelane. The difference between them consists mostly of the wide lane ambiguity, and the differential ionospheric refraction (about 0.06 cycles/TECU with the frequencies used in this work). The nondispersive terms cancel out. The main problems here are the measurement error and multipath in the carrier-phase signals. Since they are much smaller than the widelane wavelength (0.86 m), they are not likely to be an issue.

Step 3) The L_1 phase ambiguity is derived from the difference between s_1 and the unambiguous wide lane obtained previously. As before, this difference is rounded off to the nearest integer number of cycles (in this case of s_1). Once the two widelanes and L_1 ambiguities have been resolved, the resolution of those for L_2 and L_3 is immediate. Typically, the combination of carrier-phase measurement error and multipath is less than 0.2 cycles and can be ignored. The same cannot be said here of the effect of the ionosphere.

B. WARTK3

Ionospheric Corrections: In the third step of TCAR, the main problem is the differential ionospheric refraction, which can produce errors of several cycles at midlatitudes. The differential ionospheric refraction is typically more than one cycle of STEC, or 0.26 TECU for baselines longer than 10–20 km (see Fig. 1). So, if not properly corrected, it can impede proper ambiguity fixing. To avoid that, one may use, as in WARTK, a real-time model of the ionosphere. This model would be similar to the one used in meter-level augmentation systems such as (European Geostationary Navigation Overlay Service (EGNOS) or wide-area augmentation system (WAAS), but for subdecimeter carrier-phase navigation it has to meet higher accuracy requirements. The objective is to estimate the value of the differential STEC (double-differenced) between the rover and a fixed network station. In WARTK, the ionospheric refraction model is computed from dual-frequency carrier-phase GPS data from a network of ground stations, assuming a 3-D voxel description of the ionospheric region sounded by the GPS signals in the corresponding ionospheric filter. This approach reduces significantly the mismodeling of the electron content [8], [9]. The model is used, at first, to correct the widelane double-difference between stations. Then, the estimates of the corresponding L_c biases are used to find the ambiguity in the double-differenced STEC. The unambiguous STEC is then interpolated from the fixed stations to the approximate position of the vehicle, in order to make the necessary differential corrections to the data on the base-station-to-rover baseline.

The new technique, a combination of WARTK and TCAR, is called WARTK-3 (or WARTK for three frequencies). The main improvement is the use of the ionospheric correction as in the third TCAR step. So WARTK-3 can help mitigate significantly a major limitation on our ability to navigate with high precision over large areas.

III. Test and Results

A. Simulated Data

The data were generated with a modified GNSS satellite signal generator, provided by the European Space Agency (ESA) and produced in the context of a previous funded study [10]. Phase and pseudorange signals for the two GPS carriers (at 1575.42 and 1227.60 MHz) and the GLONASS channel 24 carrier (at 1615.50 MHz) were created in the GNSS simulator, with four satellites in view for 20 min using all 12 channels of an Advanced GPS/GLONAS ASIC (AGGA) validation receiver. The sampling rate was 1 Hz. These data are enough for real-time ambiguity determination using a geometry-free method, but they are very limited (just four satellites) for practical navigation purposes. The main dataset used for this study had medium signal power and multipath levels (see [10] for details).

To prove the feasibility of WARTK-3, we have studied, among others, the case of a receiver on a moving surface vehicle (SUR2). SUR2 moved along a closed circuit in a 4 km $\times$ 4 km area, at a variable speed of about 20 m/s, at a mean distance of some 129 km from the nearest reference site (REF5). Ionospheric conditions were typical for solar maximum, with considerable signal multipath in both phase and pseudorange. All fixed stations and the vehicle were situated in Germany. Ionospheric refraction was simulated for noontime, on March 17, 2000, at the solar maximum peak, using an ionospheric climatological model [11]. That replaced the much smaller refraction originally used in the simulated data, based on the Klobuchar model, at nighttime. The Klobuchar model [12] is a simple "half-cosine" function of the user's latitude, longitude, and local satellite elevation, described by eight epoch-dependent parameters fitted to a detailed global TEC model. Updated every day or so, these eight coefficients are transmitted as part of the GPS navigation message. This simple model is, on average, about 60% correct. Its purpose is to mitigate the effect of the ionosphere on data from single-frequency receivers.

In addition to the original reference receivers' datasets, three additional stations (based on actual sites from the International GPS Service (IGS) network) were simulated separately, at distances of more than 200 km from the rover, to have a wider network. In these datasets, the differential ionospheric effect between the rover and reference receivers always exceeded the 0.26 TECU limit, making it necessary to use the ionospheric corrections to resolve the ambiguities.

B. Calculations and Results

1) Ionospheric Filter: Once this filter has converged, typical errors are less than 2 TECU, as indicated by the differences between estimated and observed ionospheric delays. The filter needs 1 to 2 h from startup to converge to its full precision. At any given time, because of the round-the-clock operation of the GPS network, the filter is likely to be fully converged already. Typical frequency of update for such filter is once every 30 s for all satellite/station links, and the number of active error states at any time is of the order of 1000. In Figs. 1 and 2, one can see the differences (errors) between the double-differenced STEC for the roving receiver according to the model and the values observed at the rover (SUR2).

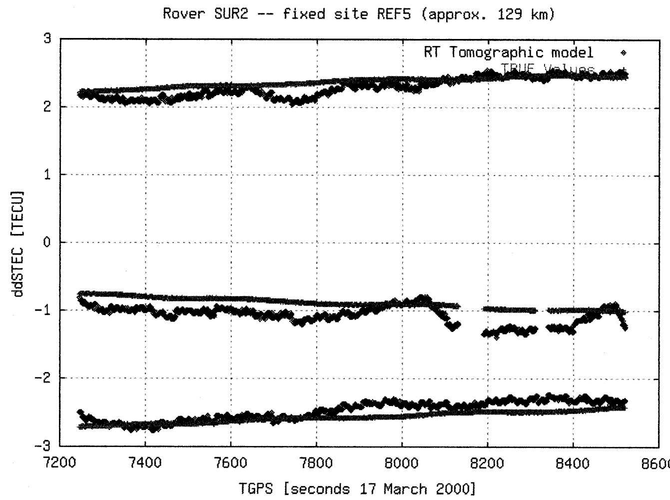

Fig. 1. Double-differenced STEC estimated in real time with the tomographic model, compared with the observed values for the surface roving receiver SUR2 referred to the most distant receiver, REF5 (about 129 km away from the rover).

Of all differential ionosphere corrections, at all epochs, 92% of have errors below the threshold limit of 0.26 TECU (horizontal lines). This is accurate enough to be able to resolve all three ambiguities in the absence of severe pseudorange multipath. Most of the 8% of estimates with errors greater than 0.26 TECU come from satellite PRN 26, that was observed at a low elevation and toward the south, where the highest ionospheric gradients take place. The use of additional stations could help overcome this limitation.

2) Ambiguity Resolution Success: A summary of the main ambiguity resolution results is shown in Table I, for a dataset with significant multipath, where the success rate at each step is indicated in three cases: 1) without ionospheric corrections (TCAR), 2) with the Klobuchar model ionospheric corrections (TCAR + Klobuchar), and 3) with the real-time 3-D voxel ionospheric corrections (WARTK-3).

3) Latency: It is important to characterize the impact of delays, or *latency*, in the availability at the rover of the ionospheric correction. After introducing simulated latency in the corrections, WARTK-3 maintained its best performance with delays of up to 5 min. Between 5 and 10 min, the success rate decreased from 90% to 85%. These numbers suggest that at midlatitude the ionospheric latency is unlikely to be an issue for WARTK-3, but would worsen with higher levels of differential ionospheric delay variation at the tropics.

4) Effect of Baseline Length: A summary of results using different reference stations is shown in Fig. 3. The baselines range from 1 km to about 130 km. The relative success in solving all three ambiguities is given as a function of distance.

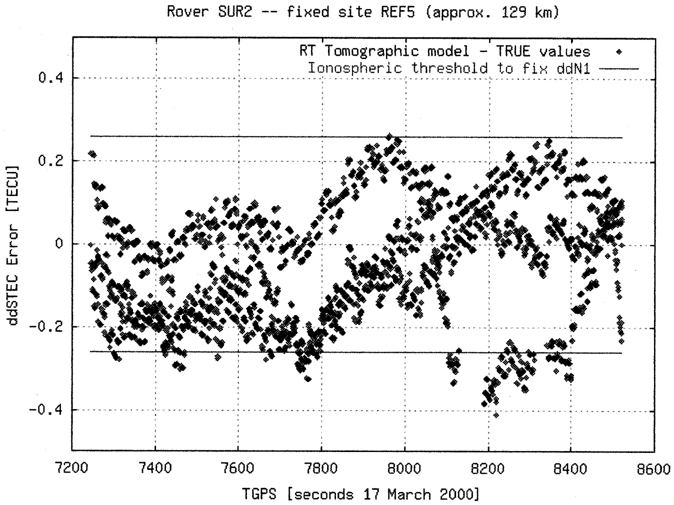

Fig. 2. Error in the real-time tomographic determination of the double-differenced STEC. More than 92% of errors fall between the critical $+/-$ 0.26 TECU levels (horizontal lines).

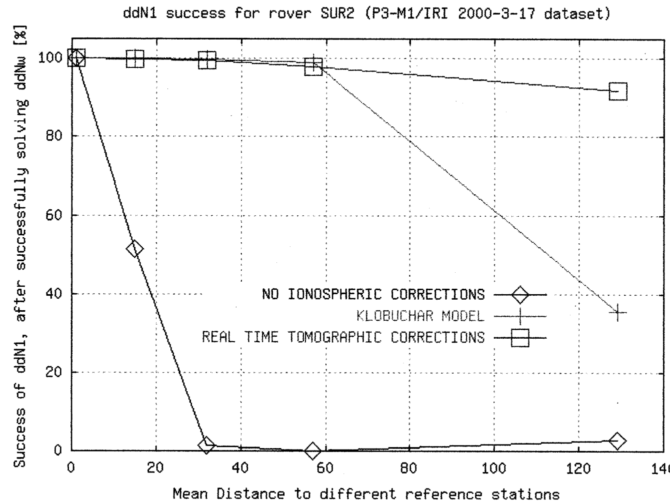

Fig. 3. Relative success of complete ambiguity resolution for the roving surface receiver SUR2, as a function of the distance to the reference station.

TABLE I

SUCCESS, RELATIVE TO THE TOTAL OF 3834 TRIALS, IN RESOLVING THE EXTRA-WIDE LANE, WIDE LANE, AND L_1 AMBIGUITIES FOR THE ROVING RECEIVER SUR2, RELATIVE TO THE DISTANT SITE (REF5, 129 km AWAY), FOR MEDIUM LEVEL OF RECEPTION POWER AND MULTIPATH. SUCCESS IS INDICATED ONLY FOR CASES WHEN ALL PREVIOUS AMBIGUITIES HAVE BEEN SUCCESSFULLY RESOLVED (IN PARENTHESIS, THE SUCCESS RATE REGARDING THE TOTAL NUMBER OF OBSERVATIONS)

SUR2-REF5 (≈129km)	Success Extra-wide lane	Success Wide lane	Success L1
Without ionospheric corrections (TCAR)	90%	95% (86)	3% (2)
TCAR+Klobuchar corrections	90%	96% (87)	35% (31)
Real-time 3D voxel corrections (WARTK-3)	90%	96% (87)	92% (79)

The simulated data all have medium power reception level, multipath, and active-ionosphere delays. It can be seen that the success decreases from 100% at 1 km to about 50% at 15 km, and to near 0% at 32 km, without ionospheric corrections. Corrections based on the Klobuchar model maintain the success rate above 95% for distances of up to 60 km. For the longest baseline (129 km), only the use of the tomographic ionospheric model yields a success rate of more than 90%.

IV. CONCLUSION

The new WARTK-3 technique, combining the three carrier-phase ambiguity resolution procedure (TCAR) with real-time tomographic ionospheric corrections, promises an instantaneous ambiguity resolution success rate of 90% or better, at distances of more than 100 km, even under difficult conditions for ionospheric modeling (noon, at solar maximum), and with ionospheric correction latencies of up to 5 min.

So, using an adequate real-time model of the ionosphere can make fast ambiguity resolution feasible over very long distances. Long-range, subdecimeter-precise navigation should become quite practical with future three-frequency systems such as GALILEO and the Modernized GPS. This ought to benefit large-area remote sensing surveys that require a very precise knowledge of sensor position.

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