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Network Differential GPS: Kinematic Positioning with NASA's Internet-based Global Differential GPS

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Abstract. Recent developments in precise GPS positioning have concentrated on the enhancement of the GPS Network architecture towards the processing of data from permanent reference stations in real-time, and the extension of the DGPS service area to the continental and global scale. The latest Global Differential GPS, as introduced by JPL, allows for seamless positioning available across the world.

This contribution presents the results of an independent experimental verification of decimeter kinematic positioning accuracy with NASA's Global DGPS system. This verification was carried out in the Netherlands, by means of both a static and a kinematic test. The standard deviations of individual real-time positions were about 10 cm for the horizontal components and about 20 cm for the vertical component. The latency of the global corrective information in the kinematic test was generally 7 to 8 seconds and more than 99% of the global corrections were available with the nominal 1-second interval.

These results confirm that single receiver kinematic positioning with decimeter accuracy is achievable by using facilities provided by the GDGPS system.

Key words: Network Differential GPS, IGDG, kinematic positioning, real-time dm-accuracy

1 Introduction

1.1 Recent trends and developments in precise positioning

Relative positioning with GPS and Differential GPS (DGPS) both involve the positioning of a second receiver with respect to a reference station. As both stations similarly experience — depending on their inter-distance — the effects of satellite orbits/clocks and atmospheric delays, the *relative* position is largely insensitive to mismodelling of these effects and their errors.

The concepts of relative positioning with GPS and Differential GPS have existed for some twenty years. Until recently, these two fields have developed relatively independently from each other. Two new trends in both DGPS positioning and GPS Real-Time Kinematic (RTK) surveying include moving from scalar corrections (from one reference station) to (state) vector-'corrections', based on a *network* of reference stations; and the processing of the data, also for the global high precision IGS-type (International GPS Service) of applications, is moving towards *real-time* execution. As a result the traditional distinction between precise relative positioning with GPS and DGPS diminishes; instead, one consistent family of applications emerges, sharing a common concept and common algorithms, that could be termed Network-based Differential GPS (NDG).

1.2 Network

Initially, systems for DGPS started with one reference station, and one or more mobile receivers (rovers) in a local area. Later, the service area of Differential GPS was extended from local to regional and national, and eventually to the continental scale with Wide Area DGPS (WADGPS) systems such as WAAS (Wide Area Augmentation System) in the US and EGNOS (European Geostationary Navigation Overlay Service) in Europe. Logically, the last step is Global DGPS, as introduced by JPL (Müllerschön et al., 2001a). Thus making seamless DGPS positioning available across the world. The advantage is that costly infrastructure is no longer needed, however, the user has to rely on the US Department of Defence (DoD) for GPS data, on a global infrastructure of active GPS reference stations, and on NASA's JPL for the corrective information.

1.3 Real-time products

The Internet-based Global Differential GPS (IGDG) system aims at real-time precise position determination of a single receiver either stationary or mobile, anywhere and anytime. The concept of Precise Point Positioning (PPP) was introduced in the early 1970s, for more details refer to the key article by Zumberge et al. (1997). Precise Point Positioning utilizes fixed precise satellite clock and orbit solutions for single receiver positioning. This is a key to stand-alone precise geodetic point positioning with cm level precision.

Over the past several years the quality of the Rapid IGS satellite clock and orbit products has improved to the cm level. Today the IGS Rapid service provides the satellite clock/orbit solutions within one day, with almost the same precision as the precise final IGS solutions (IGS, 2004). A good agreement between satellite clock error estimates produced by 7 Analysis Centers (AC) contributing to the IGS is reached. These estimates agree within 0.1 – 0.2 ns or 3 – 6 cm. Currently IGS orbits with a few decimeter precision, can be made available in (near) real-time. Ultra-rapid/predicted ephemerides are available twice each day (at 03:00 and 15:00 UT), and cover 48 hours. The first 27 hours are based on observations, the second part gives a predicted orbit. It allows one to obtain high precision positioning results in the field using the IGS products.

1.4 Dissemination of corrective information

Traditionally, DGPS-corrections are broadcast over a radio-link from reference receiver to rover. With IGDG, corrections are disseminated over the open Internet. The user can access the very modest correction data stream using a (direct and) permanent network connection, or over the public switched telephone network (PSTN), possibly using an Asynchrone Digital Subscriber Line (ADSL). For a moving user access is possible using mobile (data) communication by cellular phone (possibly General Packet Radio Service (GPRS) or the Universal Mobile Telecommunication System (UMTS) in future) or satellite phone. For commercial use three Inmarsat geosynchronous communication satellites are utilized to relay the correction messages on their L-band global beams. The three satellites (at $100°W$ (Americas), $25°E$ (Africa), $100°E$ (Asia Pacific)) provide global coverage from latitude $-75°$ to $+75°$.

2 Internet-Based Global Differential GPS

In Spring 2001, the Jet Propulsion Laboratory (JPL) of the National Aeronautics Space Administration (NASA) launched Internet-based Global Differential GPS (IGDG). Compared with traditional Differential GPS (DGPS) services, the position accuracy improves by almost one order of magnitude. An accuracy of 10 cm horizontal and 20 cm vertical is claimed for kinematic applications, anywhere on the globe, and at any time. This level of position accuracy is very promising for precise navigation of vehicles on land, sea vessels and aircraft, and for Geographic Information System (GIS) data collection, for instance with construction works and maintenance.

A subset of some 40 reference stations of NASA's Global GPS Network (GGN) allows for real-time streaming of data to a processing center, that determines and subsequently disseminates over the open Internet, in real-time, precise satellite orbits and clocks errors, as global differential corrections to the GPS broadcast ephemerides (as contained in the GPS navigation message). An introduction to IGDG can be found in Müllerschön et al. (2001a) and on IGDG (2004). Technical details are given in Bar-Sever et al. (2001) and Müllerschön et al. (2001b).

Internet-based users can simply download the low-bandwidth correction data stream into a computer, where it will be combined with raw data from the user's GPS receiver. The user's GPS receiver must be a dual frequency engine and be of geodetic quality in order to extract maximum benefit from the accurate corrections.

The final, but critical element in providing an end-to-end positioning and orbit determination capability, is the user's navigation software. In order to deliver 10 cm real-time positioning accuracy the software must employ the most accurate models for the user's dynamics and the GPS measurements. For terrestrial applications these models include tropospheric mapping function, Earth tides, periodic relativity effect, and phase wind-up, see also the review in Kouba and Héroux (2001). In addition to these models, the end-user version of the Real-Time Gipsy (RTG) software employs powerful estimation techniques for optimal positioning or orbit determination, including stochastic modelling, estimation of tropospheric delay, continuous phase smoothing and reduced dynamics estimation with stochastic attributes for every parameter.

Results of static post-processing precise point positioning are shown in, for instance, the articles Kouba and Héroux

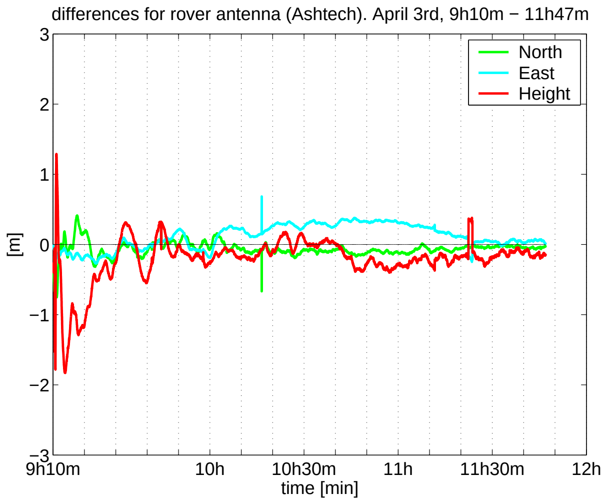

Fig. 1 Coordinate time series for the receiver onboard the boat in the kinematic test; differences with ground-truth trajectory: wet troposphere is estimated as a constant (strategy A).

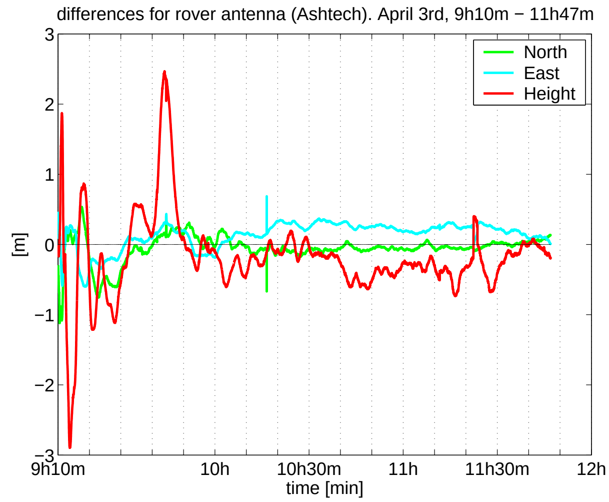

Fig. 2 Coordinate time series for the receiver onboard the boat in the kinematic test; differences with ground-truth trajectory: both wet troposphere and troposphere gradients are esimated stochastically (strategy B).

(2001) and Gao and Shen (2002). Furthermore, kinematic post-processing point positioning results can be found e.g. in Bisnath and Langley (2002).

3 Kinematic positioning with IGDG

3.1 Results

An independent experimental verification of the IGDG system has been carried out, by means of both a static and kinematic test in the Netherlands. The GPS data collected during five consecutive days (static test) and three hours (kinematic test) were processed using the filter algorithm implemented in the GIPSY-OASIS II software, see Gregorius (1996) and Gipsy (2004).

In the static test, the means of the position coordinates, taken over individual days of data, agree with the known reference at the $1 - 2$ cm level. The IGDG position solutions appeared to be free of systematic biases. The standard deviations of individual real-time position solutions were 10 cm for the horizontal components and 20 cm for the vertical component. The position coordinate estimators were correlated over about a 1 hour time span.

In the kinematic test, which was carried out with a small boat, the means of the coordinate differences with an accurate ground-truth trajectory over the almost 3 hour period were at the $1 - 2$ dm level. The standard deviations of individual positions were similar to values found in the static test, 10 cm for the horizontal components, and 20 cm for the vertical component. More than 99% of the IGDG-corrections were received with the nominal interval of 1 second, in the field via mobile communication using a GPRS cellular phone. The latency of the corrections was generally 7 to 8 seconds, for more details see Kechine et al. (2003).

The results presented in this contribution do not rely on the Internet corrections, but on the real-time JPL orbit and clock solutions instead (RTG, 2004), which are stated to be 100% consistent (Bar-Sever, 2003).

Figure 1 shows differences of the filtered position estimates for an Ashtech receiver on the boat used for the kinematic test, with a cm-level ground-truth trajectory. For this case, the wet troposphere (zenith delay) was estimated as a constant parameter for the whole time span (strategy A). The kinematic test results in figure 2 represent a strategy with both the wet troposphere and troposphere gradients estimated stochastically (strategy B). For both strategies, the initial value for the dry zenith tropospheric path delay was computed by GIPSY (a-priori model), whereas the initial value for the wet part was set to 10 cm by default. The boat coordinates were modelled as white noise; the process noise was 100 m in order to accommodate for dynamics of the boat and avoid possible divergence problems.

A comparison of these results allows one to conclude that estimation of troposphere zenith delays and gradients (as stochastic processes) in the case of single receiver precise kinematic positioning, might significantly affect filter initialization and render the filtered estimates vulnerable to various error sources capable of degrading the positional accuracy. For instance, as additional analyses showed, a peak in the Height between 9:40 and 9:50 in figure 2 is most likely caused by a deviating clock error estimate for one of the satellites in the JPL real-time ephemerides at epoch 9:45. At the same time, the peak is present in fig-

Table 1 Mean of position differences, in kinematic test; filter initialization is left out.

	North (cm)	East (cm)	Height (cm)
strategy A	−5.9	15.5	−13.1
strategy B	−2.2	18.9	−24.7

Table 2 Standard deviation of position differences, in kinematic test; filter initialization is left out.

	North (cm)	East (cm)	Height (cm)
strategy A	6.2	14.2	15.8
strategy B	8.0	12.3	20.3

ure 1, but the magnitude of the corresponding Height component deviation is noticeably decreased. Because the troposphere gradients are generally smaller than 1 cm, they have a minor impact on kinematic positioning results, and their estimation seems not to be necessary in the case of kinematic positioning at the dm level. Due to quiet tropospheric circumstances during the kinematic test the wet troposphere delay could also be left out in this case (strategy A).

In order to demonstrate how the horizontal components convergence profile is influenced by less accurate or erroneous initial position estimates, the initial values for the North and East position components were artificially shifted by 10 m, as may be the case for an approximately known initial horizontal position obtained from a standalone GPS solution for example. Analysis of the erroneous initial position results showed that the behaviour of the horizontal position component during the filter initialization in case of strategy A remained noticeably stable. The corresponding boat positioning results were nearly identical to those presented in figure 1. In the case of strategy B the large initial deviations reduced in a few minutes.

The mean and standard deviation of the position differences in the kinematic test at a 1 second interval are given in tables 1 and 2. It is to be noted that the period without the filter initialization is considered here. The first 40 minutes were not included for strategy B and the first 20 minutes were not included for strategy A.

3.2 Analysis

Additional tests were performed in order to obtain a better understanding of the kinematic positioning capabilities with IGDG, and to assess the impact of some important factors (filter convergence, GPS orbit products quality, etc) on real-time kinematic positioning. Only strategy B is considered for the kinematic test computations.

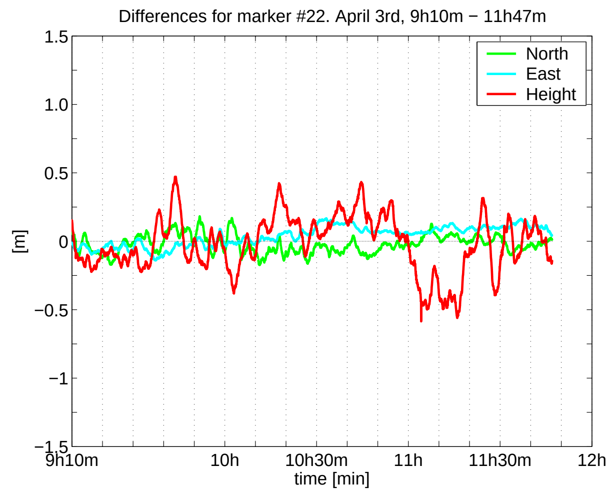

Fig. 3 Coordinate time series for the (stationary) reference station during the kinematic test; differences with the ground-truth position (strategy B).

Figure 3 demonstrates the position estimates as differences with the ground-truth position, for the (nearby) stationary reference receiver installed on a well-surveyed reference marker in Delft. Dm level accuracy is evident throughout the test period. Note the difference in scale of the vertical axis with the preceding graphs.

The kinematic processing procedure was repeated with a 5-min sampling interval in order to avoid interpolation of the JPL's Real-Time GPS satellite orbits/clocks (RTG, 2004). The positioning results for this case can be seen in figure 4. One can note that the time series is relatively smooth and without any significant variability. The standard deviations were about 5 cm for the horizontal components and 9 cm for the vertical component in case of the Real-Time GPS satellite orbits/clocks, and about 3 cm for the horizontal components and 5 cm for the vertical component in case of the JPL's Final GPS satellite orbits/clocks.

4 Further research

A number of additional tests are to be carried out to provide a better insight into the filter initialization problem in case of precise real-time kinematic positioning of a single receiver. The task is to seek fast and smooth convergence of the filtered position estimates during the first seconds after the filtering process start time. A primary interest would be to establish whether the constrained troposphere errors (taken from a-priori models) are capable of decreasing the filter convergence time. This problem can be important for regions with a high concentration of water vapour in the atmosphere and large wet delay variations (e.g. Pacific region). It is to be noted here that the

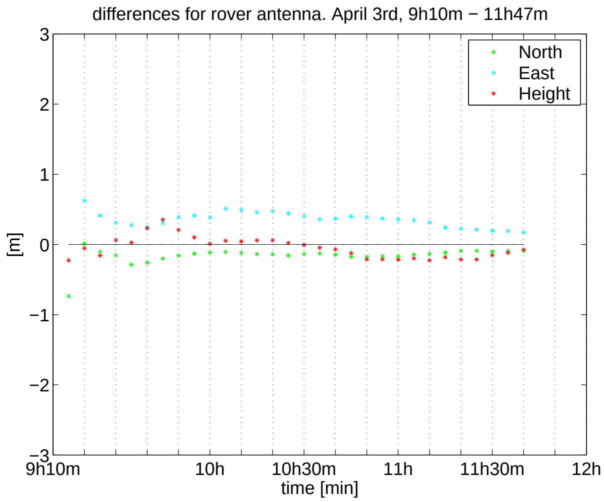

Fig. 4 Coordinate time series for the receiver onboard the boat in the kinematic test at a 5-min sampling interval; differences with ground-truth trajectory (strategy B).

kinematic test in this contribution was carried out in the Netherlands with rather moderate troposphere conditions. More GPS data should be processed in order to assess the repeatability of kinematic positioning results with IGDG, e.g. for different seasons and weather conditions. Conversely, the Precise Point Positioning approach is a potential powerful technique to obtain accurate wet zenith tropospheric path delay estimates using a single receiver.

The GPS data processing strategy adopted for the kinematic test computations requires further refinement in order to expand it to the case of a receiver with high platform dynamics (a receiver installed on a moving car, airborne and spaceborne receivers). This will allow for a comprehensive analysis of the IGDG performance for aircraft landings and takeoffs, and space kinematic applications.

The problem of single-receiver carrier phase ambiguity resolution is one of the most important and interesting challenges to be investigated in the future, and the benefits of fixing integer ambiguities to the performance of carrier phase precise GDGPS navigation require further evaluation.

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