Experimental verification of Internet-based Global Differential GPS

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BIOGRAPHY

Maxim Kechine graduated from the Saint-Petersburg State University in 1992 and obtained his PhD-degree in astrometry and celestial mechanics in 1998 at the Institute of Applied Astronomy in St. Petersburg, Russia, with a thesis on 'Regional GPS network phase data processing'. Currently he is, as a Postdoc, with the Mathematical Geodesy and Positioning section at the Delft University of Technology.

Christian Tiberius has a background in geodesy. He received his PhD degree from the Delft University of Technology in 1998 for his thesis on 'Recursive data processing for kinematic GPS surveying'. Currently he is an assistant professor with the Mathematical Geodesy and Positioning section. He is involved in several areas of GNSS positioning research as carrier phase ambiguity resolution, data quality control, analysis of geodetic-grade equipment pseudorange and carrier phase measurement noise, and evaluation of various modes of positioning and approaches for data processing.

Hans van der Marel holds a PhD-degree in geodesy from the Delft University of Technology and is currently an assistant professor with the Mathematical Geodesy and Positioning section. He was responsible for the design and set up of the permanent GPS reference station system in the Netherlands (AGRS.NL) - together with the Survey Department of Rijkswaterstaat and the Cadastre - which became fully operational in 1997. At present he is involved in GPS meteorology, in cooperation with the Royal Dutch Meteorological Institute (KNMI). He is also actively involved in national geometric infrastructure and in European reference systems (EUREF/EPN).

ABSTRACT

Internet-based Global Differential GPS (IGDG), introduced by NASA's JPL, is claimed to offer an accuracy of 10 cm horizontal and 20 cm vertical, in real-time, anywhere on Earth, at any time. An independent experimental verification has been carried out, by means of both a static and a kinematic test in the Netherlands.

In the static test, the means of the position coordinates, taken over 24 hours time spans, do agree with the known reference at the 1-2 cm level. The IGDG position solutions appear to be really free of systematic biases. The standard deviations of individual real-time position solutions turn out indeed to be 10 cm for the horizontal components and 20 cm for the vertical component. The position coordinate estimators are correlated over about a 1 hour time span.

In the kinematic test, carried out with a small boat, the means of the coordinate differences with an accurate ground-truth trajectory, over the almost 3 hour period, are 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.

Keywords: global DGPS, kinematic positioning, real-time dm-accuracy

INTRODUCTION

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 Earth, at any time. This level of position accuracy is very promising for precise navigation of vehicles on land, 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) allow 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 clock errors, as global differential corrections to the GPS broadcast ephemerides. Eventually the user can, with a dual-frequency GPS receiver, achieve 1-2 dm position accuracy in real-time.

An independent experimental verification of JPL's IGDG has been carried out at the Delft University of Technology in the Netherlands, in cooperation with the Ministry of Transport, Public Works and Water Management, Geo-Information and ICT Department (former Meetkundige Dienst van de Rijkswaterstaat). The verification consists of extensive stationary tests at a well-surveyed reference marker in Delft, and of a kinematic test using a small boat on a Dutch canal. The purpose of these tests was to verify, under practical circumstances, the real-time positioning accuracy of IGDG, as well as the availability and latency of the corrective information.

Next to a brief review of the mathematical model for the measurements and the data processing algorithm, and a description of the experiment set up, we will present in this contribution positioning results and systematic statistical analyses of both the static and kinematic test. Statistics on bias and precision of the position solution will be given, and time series of the coordinates will be shown. Temporal correlation will be assessed, as well as the relation of the position performance with the satellite geometry. An aspect that is of particular importance with kinematic positioning is the convergence of the filtered position solution after an interruption of satellite signal reception, for instance when an overhead obstruction is passed, like a bridge or a tunnel. This aspect will also be investigated in detail. Finally, results with post-processed final precise satellite orbits and clocks are compared to those obtained with the real-time products.

PRECISE POINT POSITIONING

Initially, systems for DGPS started with one reference station, with 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 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. Therewith DGPS positioning is available, seamless all over the world.

IGDG aims at real-time precise position determination of a single receiver, either stationary or mobile, anywhere and anytime. IGDG can be considered as a realization of the concept of Precise Point Positioning (PPP), see [16]. Instead of positioning relative to a reference station or network, the idea was to utilize fixed precise satellite clock and orbit solutions for *single receiver* positioning. These products are the key to stand-alone precise positioning with eventually centimeter-precision.

Results of static post-processing precise point positioning are shown in e.g. [12] and [5]. Similarly, [15] evaluates JPL's automated GPS data analysis service. Kinematic post-processing point positioning results can be found in [3]. All the above examples, and also the results in the present contribution, rely on geodetic grade *dual-frequency* receivers.

INTERNET-BASED GLOBAL DIFFERENTIAL GPS

Precise satellite orbits and clocks at the global level are provided by the International GPS Service [8]. At present, processes of determination and dissemination of these products are moving towards near real-time execution. IGS final orbit and clock solutions have a latency of 2 weeks, IGS rapid products of about 1 day, and ultra-rapid/predicted ephemerides are available twice daily. The availability of satellite orbit and clock solutions at decimeter accuracy, in real-time, enables Global Differential GPS.

A subset of some 40 reference stations of NASA's Global GPS Network (GGN) allow 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 clock 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 [14] and on [9]. Technical details are given in [1]. Tracking and latency statistics of the real-time IGDG stations can be accessed at [10]. Recently, the site and equipment used for the static test in Delft became a contributing tracking station to IGDG, known as 'dlf3', see also [13].

The results presented in this contribution do not rely on the Internet-corrections, but on the real-time JPL orbit and clock solutions instead, which are stated to be 100% consistent [2]. These real-time products by JPL include satellite position (and velocity) coordinates (in so-called Earth centered inertial (eci) format) and satellite clock error estimates, all at a 300 seconds interval.

DATA PROCESSING

The Gipsy-Oasis II software, which stands for GPS Inferred Positioning System and Orbital Analysis and Simulation System [6] and [7], has been used for processing the data of both the static and kinematic experiment. Ionospheric-free combinations of dual-frequency GPS pseudorange code and carrier phase measurements are taken as basic observables. The whole set of parameters being determined with Gipsy consists of the coordinates of the receiver's antenna, phase biases (ambiguities), site (receiver) clock biases, wet troposphere delays and horizontal gradients. The coordinates as well as the clock biases are modelled as white noise processes in time, phase biases are considered as constant float numbers, and troposphere parameters are modelled as random walk processes.

Numerous correction models are applied to the measurements in order to attain the dm position accuracy required. These models are (an indication of the corresponding maximal effect on either measurement or position is given each time in brackets): satellite antenna offsets (up to 1 m), phase wind-up (up to half a wavelength), solid Earth tides (up to 20 cm for vertical and up to 4 cm for horizontal components), ocean loading (up to 1 cm for the IGS site in Delft), polar tide (up to 25 mm for the height), sub-daily Earth rotation correction (up to 3 cm at the Earth's surface), and periodic relativity effect (up to 10 m for the ellipticity of the GPS satellites' orbits), see also the review in [12].

By default a 15 degrees satellite elevation cut-off angle was used for data processing in the static test, and 10 degrees in the kinematic test.

Though the data of the tests have been processed after data collection (post-processing), *real-time* operation has been emulated. Epochs of data have been processed sequentially and intermediate results (epoch after epoch) have been used for the analysis.

STATIC TEST

During Autumn last year, a geodetic dual-frequency receiver, an Ashtech Z-XII3 with a choke-ring antenna, was installed on a reference marker with accurately known position coordinates, see figure 1. Continuous GPS measurements have been carried out, on a neighbouring marker at this site, and these data have been, and are being processed on a weekly basis as a part of the EUREF Permanent Network (EPN) [4]. The position of this marker is well known in the International Terrestrial Reference System (ITRS), in its present realization ITRF2000. The local tie to the marker used for the static test is accurately known from earlier surveys and has been verified independently for this test. Thereby, accurate reference coordinates in ITRF2000, at the epoch of observation, were available for the static test.

Data were collected for five consecutive days at a 1 second interval. All 5 x 24 hours of data have been processed and analysed using JPL's Gipsy software, in kinematic mode, though the receiver was actually stationary.

Figure 1: The Ashtech choke-ring antenna, with conical radome, installed on the observation platform of the TU Delft building for Geodesy, for the static test. This site, about 30 meters above ground level, offers unobstructed visibility of the sky, down to the horizon, virtually 360 degrees around. The satellite elevation cut-off angle was though maintained at 10 degrees.

Position accuracy

Figures 2 and 3 present the coordinate time series, as a result of the sequential filtering process, for respectively the second and the third day of the static test. Shown are the differences, expressed in local North, East and Up, with respect to the known reference. Each day data set starts at 12:00, noon, GPS time. As the data were collected in 3 hours files, the data have equally been processed in batches of 3 hours, i.e. the filter was re-started each 3 hours with the next data-file.

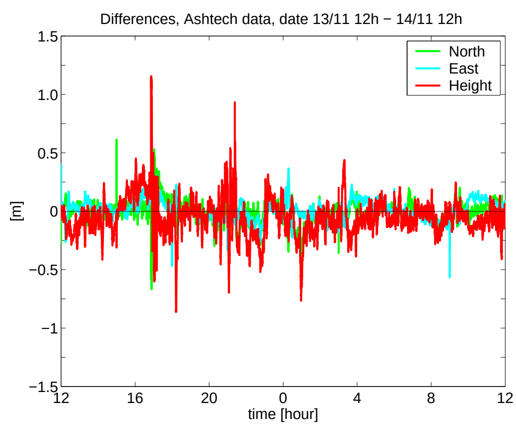

Figure 2: Coordinate time series for the second day of the static test; 24 hours at 1 second interval.

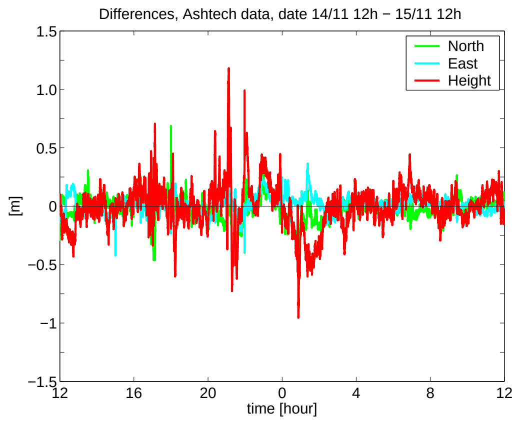

Figure 3: Coordinate time series for the third day of the static test; 24 hours at 1 second interval.

Certain similarities can be observed in the coordinate time series over the two days shown in figures 2 and 3. Most likely this is caused by the GPS satellite configuration repeating every day (minus 4 minutes) as observed at a fixed location on Earth.

The means and standard deviations of the position differences at 1 second interval, on all five days, are listed in tables 1 and 2.

day	North	East	Height
1	1.7	-1.7	-0.5
2	-0.4	0.7	-5.5
3	-2.0	1.1	-0.8
4	2.9	-1.3	-0.8
5	0.9	0.4	0.7

Table 1: Mean of position differences, in centimeter, in static test.

day	North	East	Height
1	10.1	10.4	21.4
2	8.8	8.1	16.2
3	9.5	7.0	19.1
4	12.9	11.0	22.7
5	8.7	6.7	18.6

Table 2: Standard deviation of position differences, in centimeter, in static test.

The means of the position coordinates, taken over each time one day of data, do agree with the known reference at the 1-2 cm level in the International Terrestrial Reference Frame (ITRF2000). The IGDG position solutions appear to be really free of systematic biases. The standard deviations of individual real-time position solutions turn out indeed to be 10 cm for the horizontal components and 20 cm for the vertical component. So far, earlier claims on IGDG position accuracy performance can be confirmed.

Time correlation

Figures 4 and 5 demonstrate the normalized auto-covariance functions for the daily coordinate time series of figures 2 and 3; normalized implies that the function equals value 1.0 at time lag zero. As can be seen from these graphs, time correlation in the position solution usually spans a period of about 1 hour.

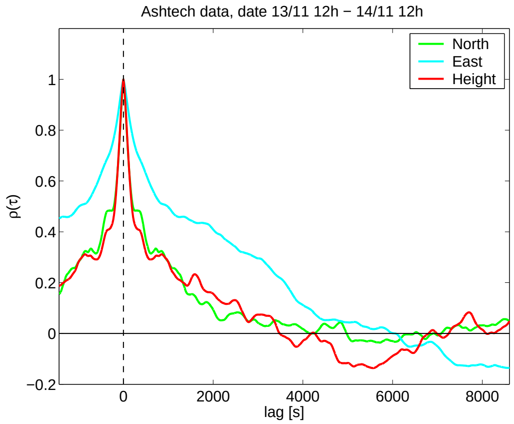

Figure 4: Autocorrelation function for coordinate time series of second day of static test; time lag in seconds.

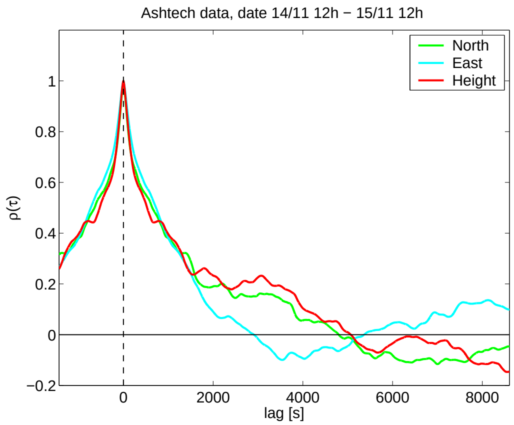

Figure 5: Autocorrelation function for coordinate time series of third day of static test; time lag in seconds.

Satellite geometry

The static test took place on five successive days. The satellite configuration repeats daily, apart from a 4 minutes shift. During the day, the number of satellites above the 15 degrees elevation cut-off angle (as used in the data processing with Gipsy) was usually in the range from 5 through 8; there were a few periods with only the minimum of 4 satellites and there was a single short period with 9 satellites.

The coordinate difference time series (at 1 second interval and obtained using JPL final orbits and clocks, see next section) of the five successive days were stacked, and standard deviations were computed, over the five days, of the coordinate differences with corresponding time of day. Figure 6 presents the standard deviations as function of time of day for the period from 9 to 12 hours (GPS time). This time of the day generally gave accurate positioning results; the level of the standard deviations is quite low, and the number of satellites in the solution is generally 7 or 8, see figure 7.

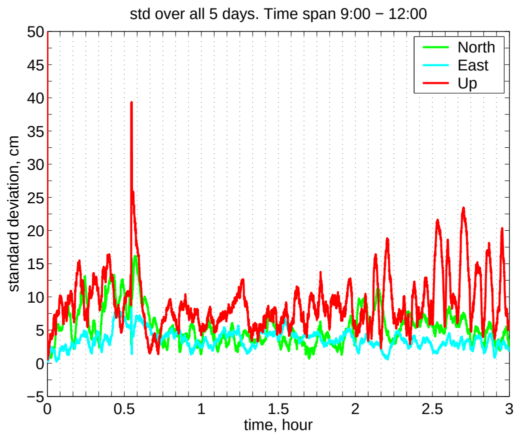

Figure 6: Standard deviation in centimeter as function of time of day.

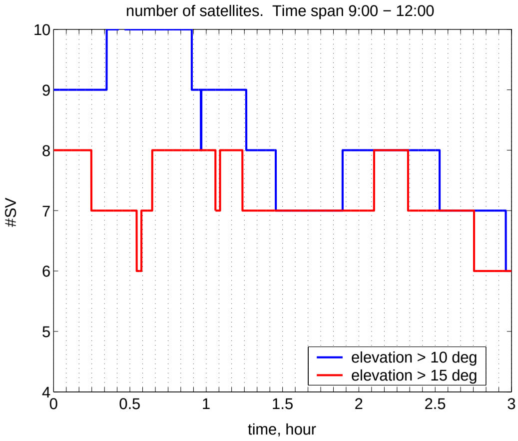

Figure 7: Number of satellites tracked (in blue, 10 degrees cut-off angle) and number of satellites used in position solution (in red, 15 degrees cut-off angle).

The short drop to 6 satellites, after about half an hour is clearly noted in the standard deviations of the position differences. The geometry during this event was not particularly poor (PDOP of about 4). Over the day, two periods occurred with only 4 satellites for which the PDOP exceeded the value of 10 (thus rather poor geometry). In these cases the standard deviation values rose up to 40-50 cm, in particular for the vertical. Next to this, it was found that also configurations with (some) satellites at relatively low elevation angles and also frequent changes in the satellite configuration (satellites disappearing, new satellites showing up) may lead to deteriorated positioning performance.

Finally, it is to be noted that satellite ephemerides are given at 5 minutes intervals and therefore vertical grid lines are shown in figure 6 with this particular interval.

Final orbit and clock products

Though only *real-time* satellite orbit and clock products are relevant to navigation applications, comparison of the positioning results with those obtained on the basis of *final* orbit and clock products, gives a first impression of the quality of the real-time products. The data of day 4 and 5 of the static test have been used, and a 5 minutes sampling interval was taken, instead of 1 second, in order to basically avoid ephemerides interpolation effects. JPL final orbit solutions [11] were used that give satellite position coordinate and clock error estimates at respectively a 900 seconds and a 300 seconds interval. Table 3 gives the standard deviations of the coordinate differences, in North, East and Height. Avoiding interpolation effects (columns real-time) causes a factor of 2 reduction in the standard deviation (cf. table 2), and using the final products (three columns at right) yields again a factor of 2 of improvement. Eventually the position coordinate estimators have an accuracy that is down at the 5 cm level. The final orbits get available only two weeks after the fact.

	real-time			final		
day	North	East	Height	North	East	Height
4	5.4	5.2	9.0	3.0	2.9	4.8
5	4.6	4.6	8.7	2.6	2.9	4.2

Table 3: Standard deviation of position differences at 5 minutes interval, in centimeter, in static test, using real-time orbits and clocks at left, and using final orbits and clocks at right.

KINEMATIC TEST

The kinematic test was carried out during Spring this year. With a small boat, see figure 8, a 2 km stretch on the Schie-canal was taken repeatedly. A trajectory of almost 3 hours has been observed, again at a 1 second interval. The trajectory is shown in figure 9. The antenna installation is shown in detail in figure 12. There were 8 to 10 satellites above the 10 degrees elevation cut-off angle and these were consequently used in the position solution (apart from two short periods with 7 satellites).

For the purpose of establishing an accurate reference trajectory for the receiver on-board, the site and equipment of the static test served as a local reference station (about 3-5 km away), and in-house software was used to compute the dual frequency carrier phase,

Figure 8: The boat used for the kinematic test on the Schie canal between Delft and Rotterdam in the Netherlands, here near the little village De Zweth.

ambiguity fixed, solution, using the data of both the stationary reference and the rover on the boat in a classical short-baseline model. The resulting trajectory, again in ITRF2000 at the epoch of observation, possesses cm accuracy, and is thereby one order of magnitude more accurate than the IGDG solution, consequently serving as the ground-truth.

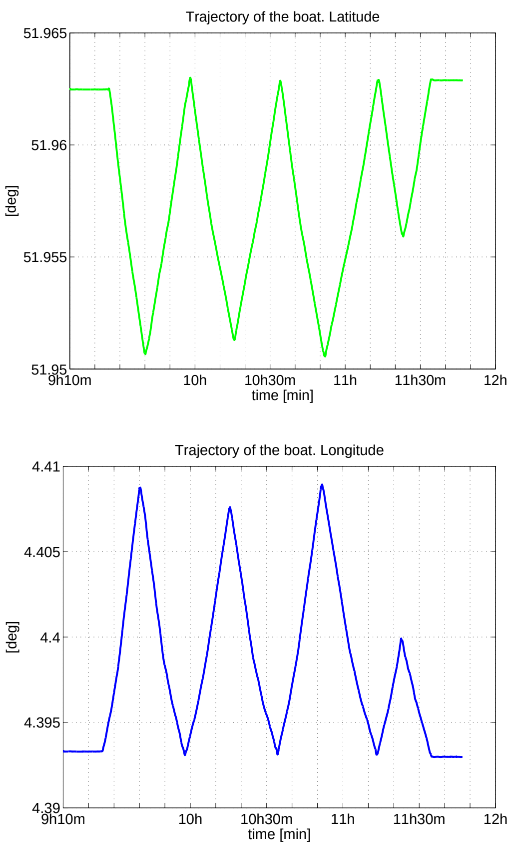

Figure 9: Trajectory of the boat in the kinematic test, latitude (top) and longitude (bottom) as function of time.

Position accuracy

Differences of the filtered position estimates for the Ashtech receiver on the boat with the ground-truth trajectory are shown in figure 10. Compared with figures 2 and 3 pertaining to the static test, the range of the vertical axis has been doubled here. Figure 11 shows the position estimates for the (nearby) stationary reference receiver over exactly the same time span.

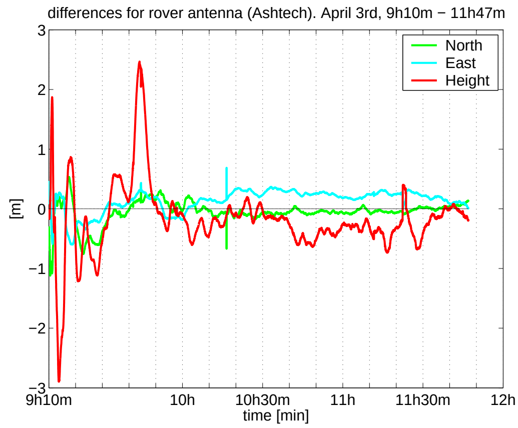

Figure 10: Coordinate time-series for the receiver onboard the boat in the kinematic test; differences with ground-truth trajectory.

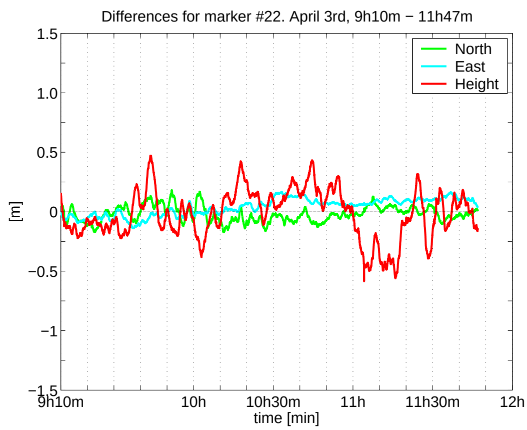

Figure 11: Coordinate time-series for the (stationary) reference station during the kinematic test; differences with the ground-truth position.

Both figure 10 and 11 show a peak in the Height component, though it is less pronounced for the stationary receiver (note different vertical scale). The peak in the Height, between 9:40 and 9:50 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.

Tables 4 and 5 give the mean and standard deviation of the position differences in the kinematic test. As can be seen in figure 10, a considerable time span is needed for achieving dm-accuracy. In tables 4 and 5, both the full period is considered, as well as the period without the 'initialization', leaving out the first 40 minutes. Apart from the initialization, the standard deviations are again 10 cm for the horizontal components and 20 cm for the vertical, but the filtered position estimates in the kinematic test appear to be slightly biased; the means over the full test period are at the 1-2 dm level.

	North	East	Height
full	-5.0	13.3	-17.2
w/o init	-2.2	18.9	-24.7

Table 4: Mean of position differences, in centimeter, in kinematic test.

	North	East	Height
full	19.1	18.9	59.4
w/o init	8.0	12.3	20.3

Table 5: Standard deviation of position differences, in centimeter, in kinematic test.

Figure 12: The choke-ring antenna installed on the boat, just above the cabin's roof. The trajectory was free of direct overhead obstructions, though visibility of the sky was partly blocked by buildings and trees directly adjacent to the water. The Schie-canal is generally 30 meter wide. The satellite elevation cut-off angle was set to 10 degrees.

Filter convergence

As can be seen in figure 10, a considerable time span is needed to achieve the dm-accuracy in kinematic applications. The kinematic test has been divided into parts and figure 13 shows two time spans of 40 minutes each, for which the position estimation was started anew (all previous data and resulting positions were simply discarded). In practice such a re-start may be needed after passing an overhead obstruction (e.g. a bridge) that causes an interruption in the reception of all satellites' signals. Generally it takes 20-30 minutes to achieve dm-accuracy for all position coordinates. In particular the Height demonstrates considerable variations during the 'initialization' period.

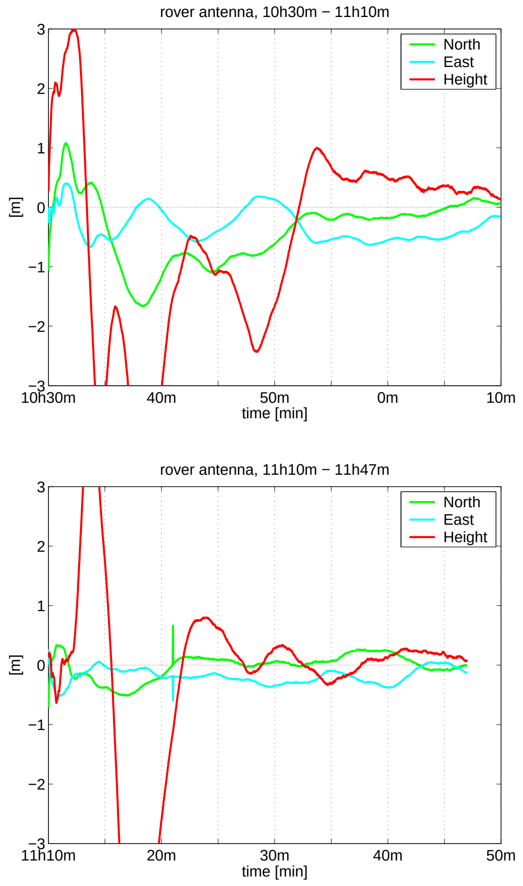

Figure 13: Coordinate time-series for two time spans of 40 minutes (10:30-11:10 on top, and 11:10-11:47 at bottom), with 're-initialization' of the filter at the beginning of the time span.

IGDG-corrections

Real-time precise positioning with IGDG is enabled through dissemination of corrections over the Internet. The corrections pertain to the satellite position (the rate of change of the coordinate corrections is given as well) and to the satellite clock error, and are to be applied to the information in the GPS broadcast ephemerides (navigation message). Correction messages are disseminated nominally at a 1 second interval. Details can be found in [1]. During the static and kinematic test the corrections have been logged and they have been analysed on the aspects of availability and latency.

Examples of the corrections are given in figures 14 and 15. The corrections for position have a smooth behaviour. The corrections usually are at the few meter level.

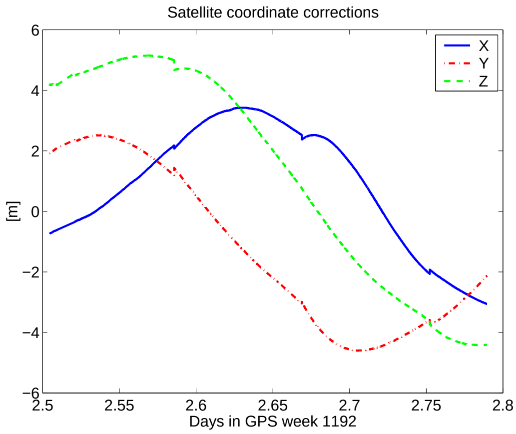

Figure 14: Position coordinate corrections for PRN01 (in meters) over the first 6 hours of the static test. The horizontal axis gives the day since start of GPS week 1192. The small jumps correspond to the change of Issue Of Data Ephemerides (IODE) for the broadcast ephemerides. The changes (renewals) take place nominally at two hours intervals.

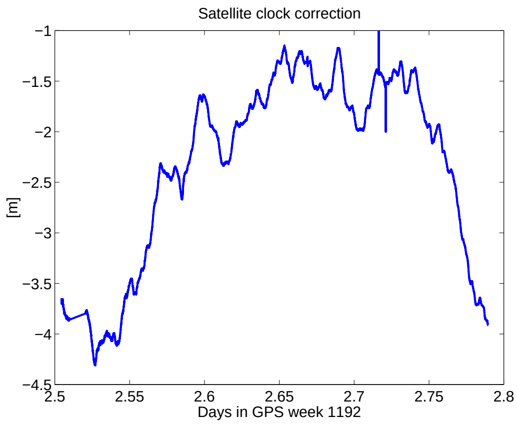

Figure 15: Satellite clock error corrections for PRN01 (in meters) over the first 6 hours of the static test. The horizontal axis gives the day since start of GPS week 1192.

During the kinematic test IGDG corrections were logged in the office over the university's network and in the field using mobile data communication by a General Packet Radio Service (GPRS) cellular phone (Nokia 6310i). A wireless Bluetooth link was established between the cellular phone and the laptop in the boat's cabin. The laptop on the boat was equipped with Windows 98SE as an operating system. In the office a stand-alone Linux PC was used. In both cases a Perl-script was used to log the IGDG-corrections.

Availability refers to the number of (1 second epoch) correction messages received (no matter the latency) as percentage of the number of epochs in the time span (i.e. the maximum possible number of correction messages).

Latency is defined here as the difference between the time of reception at the user, and the epoch of the (clock) corrections. The PC and laptop were synchronized to UTC using a secondary Network Time Protocol (NTP) timeserver. The 13 seconds difference between UTC and GPS system time have been accounted for.

In the field 99.05% of the messages were received with the expected interval of 1 second, only a few interruptions occurred spanning up to 18 missing epochs. In total 106 messages, out of 13008 (logged over a more than three and a half hour period), went missing. Using the Linux PC in the office, with a direct Internet access, availability reached up to 99.97%.

The latency of the corrections on the PC in the office was generally between 6 and 7 seconds. In the field, using the mobile data communication, the latency was 1 second larger, and generally between 7 and 8 seconds. Only incidentally, the latency reached up to 11 seconds in the field, see figure 16. These latencies are judged to be insignificant, as for instance the satellite position corrections are transmitted at a one satellite per one second message rate, in cycles of 28 seconds, and considering the rate of change in figure 15. In this respect it is to be noted that the two spikes of half a meter in figure 15 (one upward and one downward) around 2.72 days, represent each only a single value and were both identified to be most likely due to an incidental transmission error.

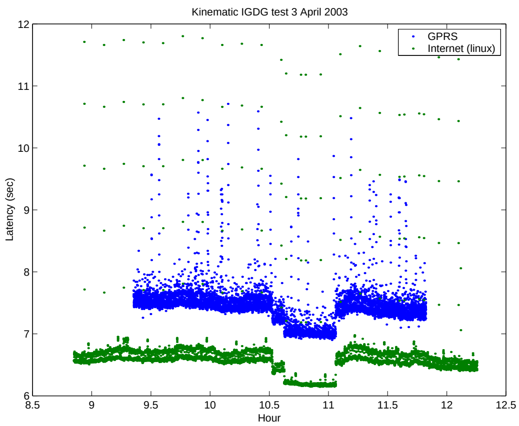

Figure 16: The latency of the IGDG-corrections during the kinematic test, in green logged in the office, and in blue in the field using mobile data communication.

In the middle both installations equally experienced a temporary decrease of about half a second in delay, during a period of half an hour. In local time, this period runs from 12:30 to just beyond 13:00.

CONCLUDING REMARKS

An independent experimental verification of Internet-based Global Differential GPS (IGDG) has been carried out in the Netherlands. Two tests were run to assess the quality of real-time position determination of a single receiver: a static test and a kinematic test, the latter with a receiver installed on a small boat. Positioning results were obtained with the Gipsy software, using the Precise Point Positioning (PPP) approach. Real-time operation was emulated in these cases.

The position solutions of the static test appear to be free of systematic biases. The standard deviations of individual real-time position solutions are 10 cm for the horizontal components and 20 cm for the vertical component. Using JPL final GPS orbit and clock products instead of real-time solutions, and avoiding the effects of interpolation, yields twice a factor of 2 of improvement in position accuracy (standard deviation). The final products become available only two weeks after the fact.

For the kinematic test, a 2 km stretch on a canal was taken repeatedly and data were collected during almost 3 hours at a 1-second interval. The position coordinates obtained with Gipsy have been compared with an accurate ground-truth trajectory. Apart from the initialization, the standard deviations are again 10 cm for the horizontal components and 20 cm for the vertical, but the filtered position estimates appear to be slightly biased; the mean of the position differences over the 3-hour test period is at 1-2 dm level.

Additional analyses have been performed to establish the time for filter convergence in the kinematic test. Generally it takes 20-30 minutes to achieve dm-accuracy for all position coordinates. The horizontal components tend to converge quite quickly, whereas the Height demonstrates considerable variations during the 'initialization' period.

To summarize, we can confirm the dm-accuracy of IGDG stand-alone receiver positioning as claimed by JPL, both in static and kinematic mode. The filter algorithm implemented in the Gipsy software demonstrated good performance for all position components of the moving receiver. Besides, the IGDG-corrections logged during the kinematic test demonstrated almost perfect availability (more than 99% of the messages were received with the expected interval of 1 second), and a latency of only a few seconds. This allows one to consider Internet-based Global Differential GPS as an efficient and reliable tool for seamless, high-precision and real-time navigation.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Y. Bar-Sever, R. Müllerschön, A. Reichert, M. Vozoff and L. Young, 'NASA's Internet-based Global Differential GPS system', *Proceedings of NaviTec*, ESA/Estec, Noordwijk, The Netherlands, December 10-12, 2001, pp. 65-72.

[2] Y. Bar-Sever, personal communication, Jet Propulsion Laboratory, Pasadena, CA, 2003.

[3] S. Bisnath and R. Langley, 'High-precision, kinematic positioning with a single GPS receiver', *Navigation*, Vol. 49, No. 3, Fall 2002, pp. 161-169.

[4] EUREF Permanent Network (EPN), Internet URL http://epncb.oma.be/, accessed May 2003.

[5] Y.Gao and X. Shen, 'A new method for carrier-phase-based precise point positioning', *Navigation*, Vol. 49, No. 2, Summer 2002, pp. 109-116.

[6] Gipsy-Oasis II software package, Internet URL http://gipsy.jpl.nasa.gov/, accessed May 2003.

[7] T. Gregorius, 'Gipsy-Oasis II: How it works …', Department of Geomatics, University of Newcastle upon Tyne, October 1996.

[8] International GPS Service (IGS), Internet URL http://igscb.jpl.nasa.gov/, accessed May 2003.

[9] Internet-based Global Differential GPS, Internet URL http://gipsy.jpl.nasa.gov/igdg/, accessed May 2003.

[10] IGDG Performance monitor, Internet URL http://galia.gdgps.net/igdg/demo/index.html, accessed May 2003.

[11] JPL Final GPS orbit & clock products, FTP-server ftp://sideshow.jpl.nasa.gov/pub/gipsy_products/2003/orbits/, accessed June 2003.

[12] J. Kouba and P. Héroux, 'Precise point positioning using IGS orbit and clock products', *GPS Solutions*, Vol. 5, 2001, No. 2, pp. 12-28.

[13] Mathematical Geodesy and Positioning section, TU Delft, Internet URL http://www.geo.tudelft.nl/mgp/ subject 'IGDG Tracking station', accessed May 2003.

[14] R. Müllerschön, Y. Bar-Sever, W. Bertiger and D. Stowers, 'NASA's Global DGPS for high-precision users', *GPS World*, Vol. 12, 2001, No. 1, pp. 14-20.

[15] B. Witchayangkoon and P. Segantine, 'Testing JPL's PPP service', *GPS Solutions*, Vol. 3, 1999, No. 1, pp. 73-76.

[16] J. Zumberge, M. Heflin, D. Jefferson, M. Watkins and F. Webb, 'Precise point positioning for the efficient and robust analysis of GPS data from large networks', *Journal of Geophysical Research*, Vol. 102, 1997, No. B3, pp. 5005-5017.