GPS, GLONASS and Galileo

GNSS Research at Delft University of Technology

As per this issue, we will regularly include special supplements in GeoInformatics that provide an overview of research activities by leading universities and research institutes from all over the world. In these reviews the invited institutes will report about the activities in their specific areas of research. Delft Technical University (the Netherlands) has the honour of being the first in this series of supplements. With four articles, the staff of the Department of Mathematical Geodesy and Positioning (MGM) will provide us with more information about their research in the area of Global Navigation Satellite Systems, GNNS for short. The head of this department, Professor Peter Teunissen, explains.

At the Delft University of Technology (DUT), research on Global Navigation Satellite Systems (GNSS) falls under the responsibility of the Department of Mathematical Geodesy and Positioning (MGP). The four research areas of MGP to which the GNSS research is linked, are: geometric infrastructure, georeferencing, geospatial modelling, and geostatistics.

Geometric Infrastructure

In the early nineties MGP took the initiative of developing an active GPS reference system (AGRS) for The Netherlands. The system became operational in late 1997, at which time the operation and management of the system was handed over to the Survey Department of the Ministry of Transport (MD) and the Triangulation Department of the Dutch Cadastre (RD). The AGRS is a permanent array consisting of five stations evenly distributed over the Netherlands. For more information on these and other applications, the reader is also referred to the internet site www.agrs.nl. Participation in the International GLONASS Experiment (IGEX-98) is another example of MGP's contribution to reference frame definitions. The IGEX-98 campaign which started in 1998 and which is still ongoing, aims to collect geodetic quality GLONASS data from a global network of stations in order to compute amongst others precise GLONASS satellite orbits and an accurate transformation between the GPS and GLONASS reference frames, see also this the article on IGEX-98.

Georeferencing

The development of the virtual reference station (VRS) concept is an example of MGP's research in the context of georeferencing. Real Time Kinematic (RTK) applications require relatively short distances to a reference station. This is mainly because the atmospheric uncertainties put a limit on the distance for which on-the-fly ambiguity resolution would still operate successfully. This distance constraint can be relaxed, when use is made of a network of reference stations. Without any aid however, this would require the user to download and process the data of all reference stations himself. The VRS concept is developed to ease this computational burden. In combination with a web-based interface, a user can download data of a non-existent – virtual – GPS reference station at a user specified position.

Geospatial Modelling

Modelling deformations due to subsidence is an example of geospatial modelling. The Groningen gasfield in the north-eastern part of the Netherlands is one of the largest in Western Europe. The subsidence caused by the extraction of gas takes place in the shape of a bowl and affects more than half of the province of Groningen. Repeated precise geodetic levelling has been conducted from the beginning of the gas production in 1964. The levelling was complemented by repeated GPS networks from 1994 onwards. On request of the NAM (Nederlandse Aardolie Maatschappij) MGP processed and analyzed the huge set of combined GPS-levelling data and developed software enabling the determination of a kinematic deformation model. This topic is addressed in the article on subsidence monitoring using GPS.

The four research areas of MGP to which the GNSS research is linked: geometric infrastructure, georeferencing, geospatial modelling, and geostatistics

Geostatistics

Historically the department has been known for its development of the quality control theory for geodetic networks (The Delft School). This theory has been extended over the past years along two parallel lines. The first extension has been the development of a quality control theory suitable for dynamic systems with real-time applications. It resulted in the recursive DIA-procedure for the detection, identification and adaptation of possible errors in the observation- and/or dynamic model of a Kalman or least-squares filter. Since its introduction, the DIA-procedure has been in use for a variety of different applications, such as the integrated ship bridge concept (Bridge-2000), marine seismic networks and integrity monitoring of GNSS reference stations.

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1 GPS Meteorology and Atmosphere Modelling

The Earth's atmosphere is one of the limiting factors for precise positioning using Global Navigation Satellite Systems (GNSS). More than once, geodetic engineers must have wished the Earth were without an atmosphere, so that the satellite signals are not retarded and bended in unpredictable ways. However, these engineers learned to live with it by developing methods that eliminate these disturbing effects from the measurements, and what was once a nuisance has now become a well-appreciated signal.

By Frank Kleijer, Hans van der Marel, Dennis Odijk and Inseong Song

The atmosphere is composed of a neutral and ionized part, which affect GNSS signals differently. The bulk of the neutral atmosphere is located in the lower 10 kilometres of the atmosphere. This part causes GNSS signals to delay by roughly 2.5 metres in the zenith direction, and about 10 metres at lower elevations. This is the so-called tropospheric delay. The tropospheric delay is the same for all the frequencies at which GNSS satellites operate. It can be modelled with an accuracy of about 10 centimetres, which is sufficient for most navigation applications, but not for precise positioning applications.

Ionospheric Delays

Above altitudes of 100 kilometres the Earth's atmosphere is ionized which causes the so-called ionospheric delay of GNSS signals. The delay depends on the amount of free electrons along the signal path and the frequency of the signals (the delay is dispersive). The solar activity influences the degree of ionization. A maximum is reached typically two hours after local noon. There is also a seasonal and spatial variation. The delay is typically in the range of 10 to up to 100 meters, depending on the degree of ionization and satellite elevation. Therefore, this is an effect every GNSS user has to take into account.

Eliminating the Effects

By using dual frequency GPS receivers it is easy to eliminate the ionospheric delay with a linear combination of the observations. However, this is a very costly operation: it increases the noise and multipath error in the measurements by a factor 3. Furthermore, the use of the linear combination makes it much more difficult to retrieve the integer phase ambiguity parameters. This is a major drawback for short observation periods, but for continuously operating GPS receivers in regional and global networks, the advantage of eliminating the ionospheric effects completely outweighs the disadvantages.

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Short Baselines

For short baselines it is not necessary to eliminate the ionosphere using dual-frequency measurements, because forming between-receiver single-difference observations reduces the effect as well. The integer nature of the double-difference phase ambiguities is preserved, and this can be used to get centimetre accuracy in the positioning, while using relatively short observation times of several minutes (see for instance the LAMBDA-method described in the "GNSS carrier phase ambiguity resolution" contribution). This works well for distance up to 10-40 km, depending on the degree of ionization in the ionosphere. When the reference receiver and rover are both equipped with near real-time communication links (like radio modem or GSM) the position of the rover can be computed in almost real-time (RTK-GPS). Much of the research at Delft University (MGP) is directed towards extending the distance over which RTK-GPS can be used and improving the reliability of this technique. This is done in part by developing more sophisticated models to estimate the ionospheric delay, using basically a stochastic modelling approach. Another approach is to use a network of permanent GPS receivers to predict the ionospheric delays for the rover, like is done in the virtual GPS reference station approach. Linear combinations of dual-frequency measurements can also be used to estimate the ionospheric delay. Using these, the Total Electron Content (TEC) and differential signal delays in the satellite and receiver hardware can be computed. Several institutes now compute TEC maps on a routine basis and show them on the Internet.

Tropospheric Delay Estimation

In order to compute accurate positions from GPS, geodetic engineers compute the deviation of the actual signal delay, caused in part by the atmosphere, and interpret this delay in terms of tropospheric zenith delays. The tropospheric zenith delay can be separated from other parameters, like the receiver clock error and station height, because in general satellites are visible at different elevation angles. The relation between the measured signal delay and tropospheric zenith delay is known; this is the so-called mapping function. The tropospheric zenith delay consists of a hydrostatic and wet component. The hydrostatic component of the total zenith delay can be computed from surface pressure measurements. The remainder, the wet component, is attributed to water vapour. The wet delay is highly variable and cannot be predicted with sufficient accuracy from ground based meteorological measurements. Therefore, geodetic engineers often treat the wet delay components as unknown parameters and estimate it in a least-squares adjustment along with other parameters. Typically, one parameter per station is estimated once every 6 minutes to two hours, depending on the application. The troposphere is a factor that limits the accuracy of the GPS height estimates.

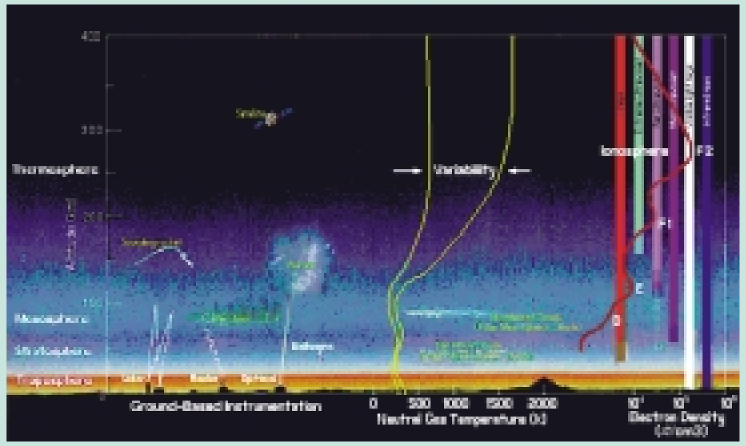
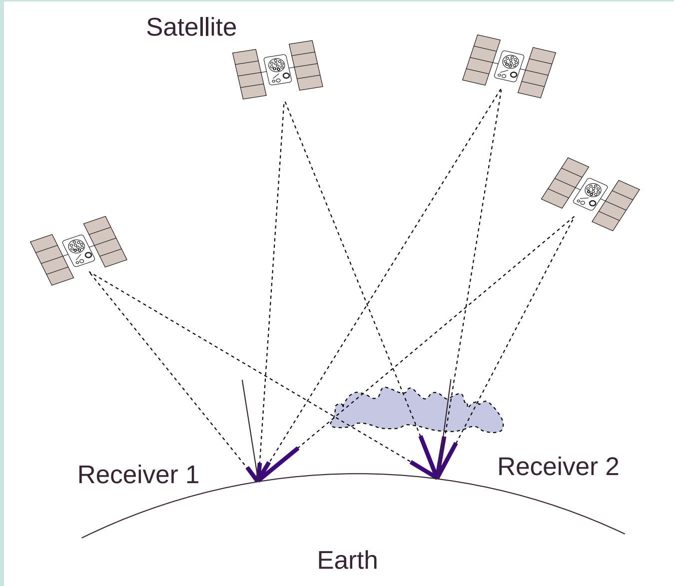


Illustration of the upper-atmosphere temperature variability and the regions of Earth's ionosphere, which are labeled by letters. The various ionospheric peaks are the result of the various sources of atmosphere ionization and the atmospheric chemistry at different altitudes. Image courtesy of J.H. Yee and associates, Applied Physics Laboratory, Johns Hopkins University.

GPS Meteorology

Geodesists usually don't use the tropospheric wet delay estimate but treat it as a nuisance parameter. However, these estimates contain valuable information for meteorologists because the amount of water vapour in the atmosphere can be derived from it. Using the mean temperature of the atmosphere, integrated water vapour (IWV) can be computed from the zenith wet delay. Integrated water vapour is typically expressed in kg/m2, whereby 1 kg/m2 corresponds to roughly 6.5 mm zenith wet delay. The actual process is slightly more complicated because GPS is basically a relative measurement technique. It is therefore only possible to observe tropospheric delay differences between stations. Only in a network, that spans a large part of the Earth, it is possible to estimate absolute delays because due to the curvature of the Earth, stations receive signals from the same satellite at different elevation angles.



GPS signals are retarded by atmospheric water vapour

> *There is a trend towards near real-time networks for real-time kinematic GPS (RTK-GPS) applications and meteorology*

Climate Applications

GPS can be used successfully to derive the integrated water vapour content in the atmosphere. Studies continue to improve the accuracy and limit the biases of the estimates, which are very important from the viewpoint of climate applications. At the same time, several international projects have been started to demonstrate the possibility to use GPS in near real-time to estimate IWV for numerical weather prediction (NWP) applications. The potential of GPS for use in NWP is large, provided IWV measurements are available in a time frame of 1-2 hours. Nowadays, more and more GPS permanent stations make their measurements available in near real-time, which is an important development not only for meteorological applications, but also for network RTK.

Future

Permanent GPS networks are more and more used for other applications than geophysical monitoring. There is a trend towards near real-time networks for real-time kinematic GPS (RTK-GPS) applications and meteorology. New applications of GPS have emerged in meteorology and work is now ongoing to use GPS as an operational system for Numerical Weather Prediction applications. Due to the increased interest and applications, GPS networks are growing and become denser than ever before.

Interesting URL's:
www.knmi.nl/onderzk/atmoond/GPS/index.html

www.gst.ucar.edu/gpsrg/

www.nottingham.ac.uk/~iszwww/isgres30.html

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2 The International GLONASS Experiment -IGEX 98

The integrated use of GPS and GLONASS offers a number of distinct advantages in terms of precision, reliability and availability. In order to benefit from such an integrated system, a number of problems have to be solved as well. For example, GPS and GLONASS not only use different datums, but also different time systems. Therefore, in 1998 the International GLONASS Experiment (IGEX98) was started. In this experiment a global tracking network collects data from the GPS and GLONASS satellites, which is processed by a number of analysis centers.

By Kees de Jong, Niels Jonkman, Marina Martínez-Garcia

IGEX-98 is sponsored by the International Association of Geodesy (IAG), through its commission on International Coordination of Space Techniques for Geodesy and Geodynamics (CSTG), the International GPS Service (IGS), the Institute of Navigation (ION) and the International Earth Rotation Service (IERS). The experiment started on October 19, 1998 and was officially terminated on April 19, 1999. Since April 20, 1999 IGEX-98 continues on a best effort basis.

Main Objectives

The main objectives of IGEX-98 are:

- Set up a global GLONASS tracking network
- Test GLONASS data processing software
- Determine precise GLONASS orbits and gain insight in the GLONASS orbit modeling peculiarities
- Study common GPS/GLONASS processing strategies
- Determine transformation parameters between WGS84 (used by GPS) and PZ90 (used by GLONASS)
- Establish the relationship between the GPS and GLONASS time systems
- Compare receiver equipment performance
- Foster participation and cooperation with Russian organizations

Since the GLONASS satellites are equipped with corner cube reflectors, another objective of IGEX-98 is to engage the collaboration of the SLR (Satellite Laser Ranging) community, for comparing the orbits determined using microwave tracking with those obtained using SLR. In August 1998, the Russian Space Agency granted permission to track the

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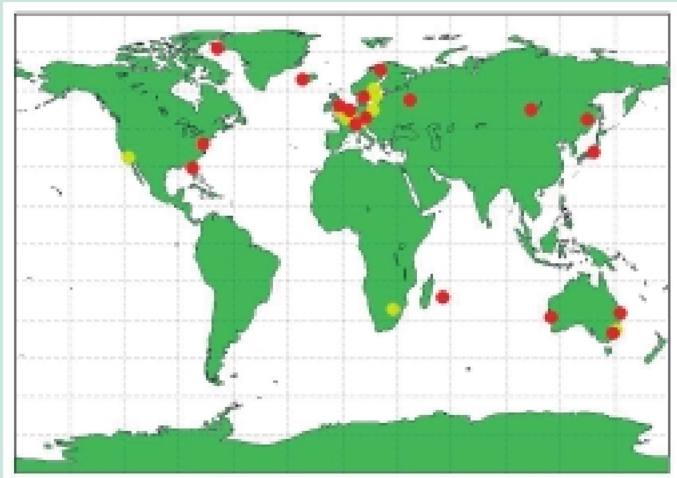
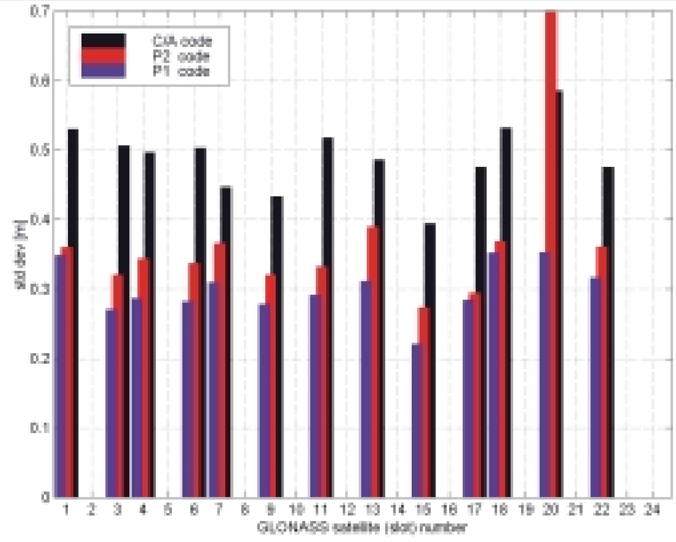


Map of the IGEX-98 tracking network



Average estimated precision of C/A, P1 an P2 code observations

GLONASS satellites by means of SLR equipment.

Components

IGEX-98 consists of a number of components. The most important are the tracking network, data centers, analysis centers and an e-mail based information service. During the official period of IGEX-98, the tracking network consisted of approximately 60 sites. Not all of them were collecting data simultaneously. The tracking stations make their data available to one of five regional data centers, which in turn send the collected data to two global data centers. At the global data centers the data will be archived and made available for further processing. Five analysis centers process the data of (a subset of) the tracking network, to determine the parameters of interest. A summary of the results is distributed by e-mail to those interested. In September 1999, prior to the ION GPS '99 meeting in Nashville, an IGEX-98 workshop was organized. At this workshop researchers from all over the world were given the opportunity to present and discuss the results, obtained using data from the campaign.

IGEX-98 Results

- GLONASS Orbits

The original aimed for precision of the GLONASS orbits was at the level of one meter. During the course of IGEX-98 it appeared already to be possible to determine GLONASS orbits with a precision of about 20 centimeters, from dual-frequency code and carrier observations. This figure is amongst others based on a comparison between SLR and microwave tracking results. During the official part of IGEX-98, nine GLONASS satellites were also tracked using SLR techniques. It appeared that there is a small bias between the orbits derived using SLR and those using microwave tracking. The source of the bias is not yet known. For GPS the orbits can be determined with a precision which is at the sub-decimeter level. It is expected that more sophisticated models will eventually result in GLONASS orbits of similar quality. The difference between the GPS and GLONASS time systems seems to be biased by receiver delays, which may amount to one microsecond.

- GLONASS P-code

The GLONASS P-code is freely available to civil users. GLONASS P-code measurements are more precise than C/A code observations from either GPS or GLONASS. This offers advantages in time transfer applications. Reported time transfer precisions are of the order of 2 parts in 10^{15} over one day or 200 picoseconds per day. A precision of 1 part in 10^{15} over one day seems feasible in the near future.

- WGS84 and PZ90

Several sets of parameters for the transformation between WGS84 and PZ90 have already been determined. These sets consist of one scale factor, three translations and three rotations. The most significant parameter seems to be the rotation around the z-axis. The final set of transformation parameters is not yet available.

GPS/GLONASS Receivers

Some of the GPS/GLONASS receivers used during IGEX-98 had only recently come to the market. As a result, a number of firmware upgrades were provided during the campaign. It became apparent from the analysis that each upgrade improved receiver performance. It also became clear that, although the hardware is maturing, tuning is still required: one upgrade improved the precision of the observations, but resulted in an increased number of cycle slips, whereas for another upgrade it was the other way around. The receiver installed at DUT tracks all visible satellites, even when they are set unhealthy. It appeared that for GLONASS it sometimes occurs that a satellite is set unhealthy, but that it keeps transmitting good data (code and carrier observations, orbital and clock parameters) for more than one month. This is significant with the current constellation of only eleven healthy satellites.

Observations

The estimated standard deviations of the code observations of the GLONASS observations are of the order of 0.5 m or better. These estimated values depend on the receiver itself and its location. Effects due to multipath are hard, if not impossible, to avoid. The GLONASS satellite ground tracks are repeated after eight days; multipath effects in the estimated standard deviations

Some of the GPS/GLONASS receivers used during IGEX-98 had only recently come to the market. As a result, a number of firmware upgrades were provided during the campaign

of the code observations therefore also have a period of eight days.
The number of cycle slips in the GLONASS carrier data is small. Except for a few healthy satellites, which are known to

The Department of Mathematical Geodesy and Positioning (MGP) of Delft University of Technology (DUT) has been involved in IGEX-98 since the beginning of the experiment. Delft is one of the stations of the IGEX-98 global tracking network. The dual-frequency GPS/GLONASS receiver at this station is made available by the Survey Department of the Ministry of Transportation and Public Works, which is the main sponsor of MGP's GLONASS research.

transmit bad signals, cycle slips occur only at low satellite elevations.

Future of IGEX-98

According to the IGEX-98 steering committee, IGEX-98 was successful beyond expectation. A vast majority of the participants of the IGEX-98 workshop in Nashville were in favor of a continuation of the experiment. It was therefore decided to extend IGEX-98 until 2003. As already mentioned, currently IGEX-98 continues on a best effort basis. As a result, the experiment has lost some of its momentum and the number of dual-frequency receiver in the global tracking network has decreased to about 20. In order to the extended campaign to be meaningful, it was urged that the tracking network be extended and provide a balanced global coverage. A new call for participation in IGEX-98 will be prepared and distributed in the near future.

URL IGEX-98:
http://lareg.ensg.ign.fr/IGEX/

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3 GNSS Carrier Phase Ambiguity Resolution

There exists a great variety in Global Navigation Satellite System (GNSS) positioning applications. Although all the GNSS models behind these applications may differ greatly in complexity and diversity, they all have in common that their problem of carrier phase ambiguity resolution is intrinsically the same. Hence, once a rigorous theory of ambiguity resolution is available, there is no need to design or formulate 'new' methods of ambiguity resolution for each new application. In this article we will briefly outline the elements of ambiguity resolution and exemplify that the rigorous theory on which the LAMBDA method of ambiguity resolution is based, make this method also applicable and suitable for the future three frequency satellite navigation systems, such as the modernised GPS and the European Galileo system.

By Niels Jonkman, Peter Joosten, Peter Teunissen

Why Ambiguity Resolution?

Of the two GNSS observables, the pseudorange and the carrier phase, the carrier phase is by far the most precise. It has, however, one Achilles' heel: the initial measurements of the carrier phases of the GNSS signals received by a receiver as it starts tracking the signals are undetermined, or ambiguous, by an integer number of carrier wavelengths. A GNSS receiver has no way of distinguishing one carrier cycle from another. The best it can do is measure the fractional phase and then keep track of phase changes. Therefore, the initial unknown integer ambiguities must be determined from the GNSS data. This process of resolving the unknown cycle ambiguities of the carrier phase data as integers, is referred to as ambiguity resolution. It is the key to fast and high precision GNSS positioning. Once the integer ambiguities have been successfully resolved, the carrier phase measurements will start to act as if they were high precision pseudorange measurements, thereby allowing the remaining parameters, such as the position coordinates, to be determined with a comparable high precision. Figure 1 shows the effect on baseline repeatability of successful ambiguity resolution.

Method of Ambiguity Resolution

The great variety in GNSS positioning becomes apparent when one considers the diversity in applications. They range from short single-baseline applications, such as real-time kinematic (RTK) positioning, to long range multi-baseline networks used as a tool for studying geodynamic phenomena, or from super short multi-baselines used for local attitude determination, to wide-area systems of reference stations used for transmitting differential corrections. For these different applications, various methods of ambiguity resolution have been devised and proposed in the past. It will become clear however, that there is no need for different methods of ambiguity resolution, once the conformity in these different applications is recognized.
The general procedure for determining the ambiguities can be divided in two steps (figure 2). In the first step one adjusts the GNSS measurements for the unknown ambiguities along with other unknowns, like the position parameters. From this step results a real-valued ambiguity estimate. Then in the second step the real-valued ambiguity estimate is mapped into an integer. This integer is the integer ambiguity estimate. Although various methods have been proposed over the years to carry out the two steps, there do exist optima or best methods for both steps. The optimum for the first step is well-known: it is least-squares adjustment. Least-squares adjustment is optimal in the sense that it provides the most precise estimates for the real-valued ambiguities. The best method for the second step is less well-known: it is integer least-squares adjustment. Integer least-squares adjustment is best in the sense that it yields the highest possible chance of mapping the real-valued ambiguities to the correct integers. A very efficient algorithm to carry out the integer least-squares mapping is the LAMBDA method.

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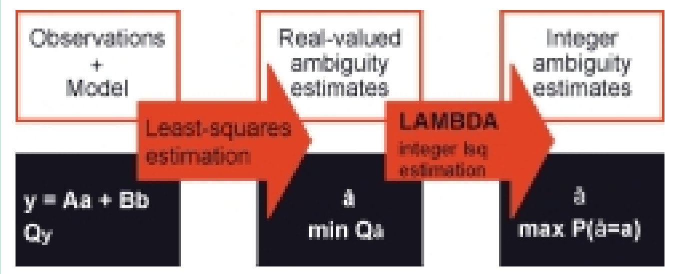

Figure 2: Two-step procedure for determining the integer ambiguities. The real-valued ambiguities, as determined from a least-squares adjustment, are mapped by the LAMBDA method to the optimal integer ambiguities.

Reliability of Ambiguity Resolution

It is of course not enough to compute the integer ambiguities and be done with it. One can always compute such a solution, whether it is of good quality or not. One therefore still needs to address the question whether one has enough confidence in the computed integer ambiguity solution. After all, unsuccessful ambiguity resolution, when passed unnoticed, will all too often lead to unacceptable errors in the positioning results. One therefore needs to have a way of knowing how often one can expect the computed ambiguity solution to coincide with the correct, but unknown, solution. Is this 9 out of 10 times, 99 out of a 100, or a higher percentage? It will certainly never equal 100%. After all, the integer ambiguities are computed from the data: they are therefore subject to uncertainty just like the data are.
In order to be able to predict the reliability of ambiguity resolution, the concept of the ambiguity success rates was developed. The success rate describes the probability of correct integer ambiguity determination and it can be computed for any GNSS application. Its value lies between zero and one, and it depends on all system parameters that influence the performance of ambiguity resolution, such as, measurement precision, sampling rate, observation time span, number of satellites tracked, receiver-satellite geometry, etc. Only when the success rate is close enough to one, can one expect ambiguity resolution to be successful.

GNSS Ambiguity Success Rates

GPS satellites currently transmit signals on two frequencies. The future GPS block IIF satellites however, will transmit signals on three navigation frequencies and the same holds true for the proposed European satellite navigation system Galileo (figure 4). Although the actual GPS frequencies have already been established, this is not yet the case for the proposed Galileo system. It is therefore of interest to study the effect on ambiguity resolution of varying the spacing between the frequencies. As a design tool, the success rate is particularly suited for this task. The instantaneous long baseline geometry-free GNSS success rates are shown in figure 5 as function of the location of two of the three frequencies. From the figure one can see that the success rates are even in the most favorable case smaller than 25%. Hence, even with the third frequency, instantaneous long baseline ambiguity resolution will still not be reliable. However, depending on the choice of frequencies, a considerable improvement over two frequency ambiguity resolution can be achieved. The long baseline GPS two frequency success rate is indicated in the figure with a red contour line. Choosing the second and third frequency in the blue area within this contour line yields less reliable ambiguity resolution, while all other combinations give more reliable ambiguity resolution.

> *There is no real need for using and developing different methods of ambiguity resolution. This also holds true for the future three frequency global navigation satellites systems such as GPS and Galileo*

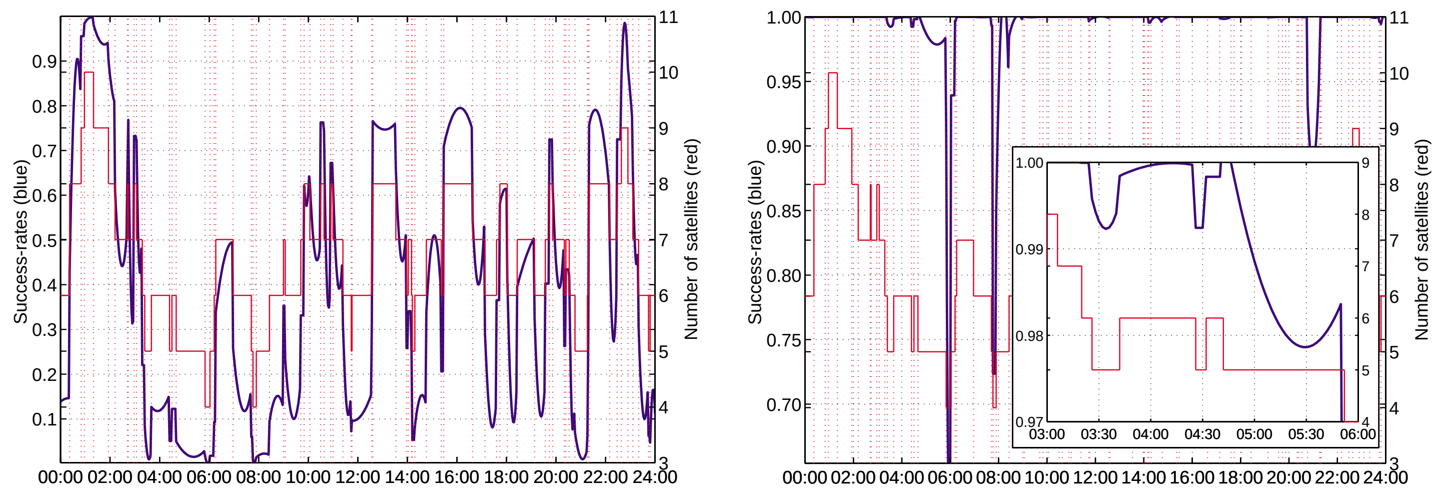

Figure 3: Ambiguity resolution success rate for single frequency and dual frequency GPS observations, left and right figure respectively. The figures show the variations of the success rates and the number of visible satellites on June 6th, 1999. A success rate of 1 indicates that all integer ambiguity estimates are correct, a success rate of 0 indicates that none of the integer estimates is correct.

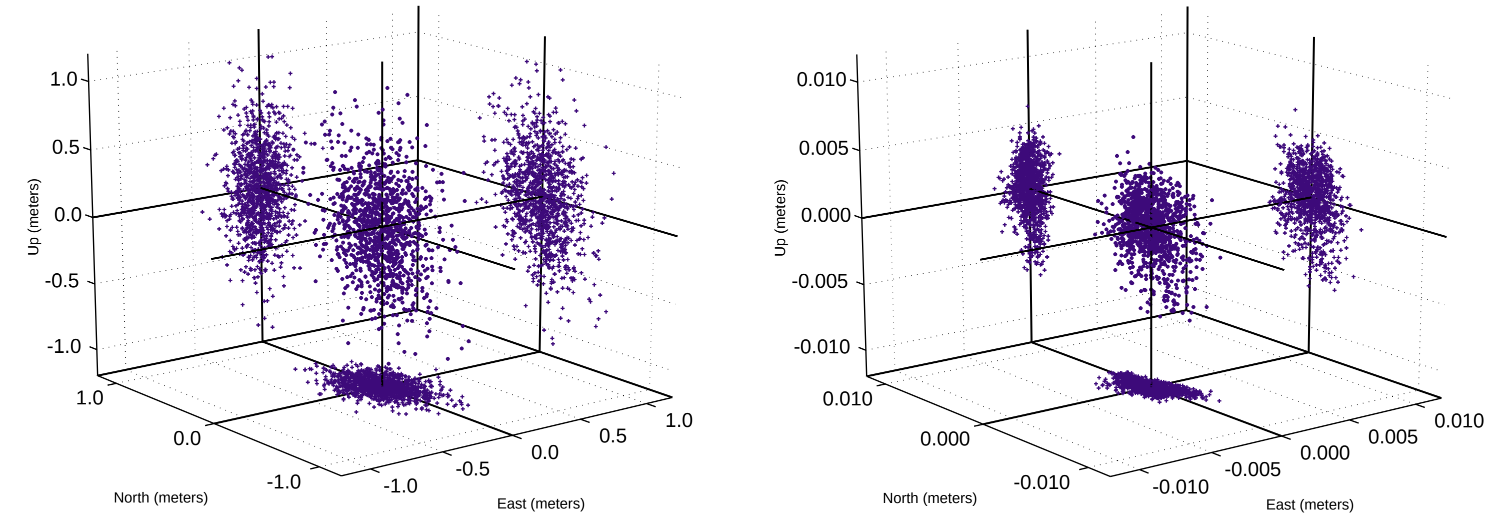

Figure 1: Two three-dimensional scatter plots of position (North, East, Up) describing the repeatability of instantaneous, dual-frequency GPS baseline determination as obtained with (right) and without (left) the use of ambiguity resolution. Note that ambiguity resolution improves the precision of the position coordinates by a factor of 100. These results were obtained with the LAMBDA (Least-squares AMBiguity Decorrelation Adjustment) method as developed at DUT. Several independent and international studies have highlighted the excellent performance of the method. The method is implemented in various GPS software packages and is currently in use at more than one hundred institutes worldwide. More information on the method can be found at http://www.geo.tudelft.nl/mgp

The approximate location of the GPS second and third frequency and a likely candidate for the Galileo frequencies are also indicated in the figure. Although they will achieve an improvement over the two frequency case, it appears that one would be better off by spacing the frequencies further apart.

Conclusion

It has been emphasized that a rigorous theory of ambiguity resolution is presently available. Optimal carrier phase ambiguities are obtained by means of integer least-squares, their reliability is described by means of the success rate, and an efficient implementation is provided for by the LAMBDA method. There is therefore no real need for using and developing different methods of ambiguity resolution. This also holds true for the future three frequency global navigation satellites systems such as GPS and Galileo.

	F1 (MHz)	F2 (MHz)	F3 (MHz)
GPS2	1575.420	1227.600	-
GPS3	1575.420	1227.600	1176.450
GNSS-2	1589.742	1561.098	1256.244

Figure 4: Current and future GPS signal structure together with the likely Galileo candidates.

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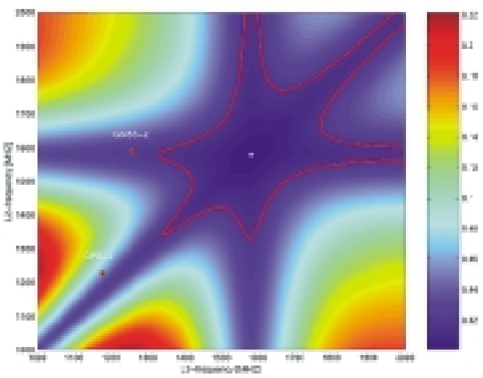

Figure 5: Instantaneous long baseline GNSS ambiguity success rates as function of the location of two of the three frequencies. One frequency is fixed to 1580 MHz, which is approximately equal to both the GPS L1 and the Galileo E1 frequency, while the two other frequencies vary between 1000 and 2000 MHz. The success rates in the figure are coded with colors: red for large success rates, blue for small success rates.

4 High Precision Subsidence Monitoring Using GPS

Land subsidence due to gas exploration is a slow and gradual process that can only be monitored over large time spans by high accuracy measurements over a wide area and requires scrupulous data processing. Repeated leveling campaigns have proved to be very adequate for this purpose. For absolute deformation analysis the leveling networks have to be connected to stable reference benchmarks outside the subsidence area, thus requiring extended leveling networks. Therefore, despite the known fact that the accuracy of GPS heights can hardly compete with leveling, it is expected that subsidence monitoring could benefit from GPS in a number of ways:

- **GPS is a fast and relatively inexpensive method when compared to leveling;**
- **GPS can bridge long distances easily, also over bodies of water, e.g. to provide ties to far away reference benchmarks outside the subsidence area;**
- **GPS would be a second, independent method, making it possible to assess possible systematic effects in the leveling.**

The Delft University of Technology processed data of the GPS and leveling campaigns, as measured for monitoring land subsidence above the Groningen gas field. This gas field, located in the north-east of The Netherlands, is considered as one of the largest and most compact ones in the world. The aim was to fully access the accuracy of the data and to establish the most adequate processing method.

Frank Kenselaar, Marcel Martens

Combining Spirit Leveling and GPS

The main concern is whether GPS can provide the necessary sub-centimeter accuracy for this kind of deformation analysis, especially because GPS derived heights are known to be less accurate than the horizontal components. Another problem is that GPS produces ellipsoidal heights, whereas a leveling survey yields orthometric or normal heights. Combining GPS and leveling heights requires the availability of accurate geoid separation values. However, if one is only interested in deformation, it is possible to combine height changes in time derived from GPS with leveling. The geoid separation can then be eliminated if it is assumed constant in time. Theoretically, the geoid separation is changed by the exploitation of the gas field. Since this geoid change has a very small magnitude over a very long time span the effect can usually be ignored.

Subsidence Monitoring of the Groningen Gas field

Since 1964 natural gas is extracted from the Groningen gas field in the north-east of the Netherlands. This is one of the largest and most compact gas fields in the world. Gas extraction resulted in reservoir compaction and consequently surface subsidence with a maximum of 1 cm per year. Since large parts of the Netherlands, including Groningen, are situated below sea level surface, land subsidence has serious consequences for the water management systems in the area, making additional investments in sluices and pumping stations necessary. The producing oil company, the Nederlandse Aardolie Maatschappij (NAM), has to compensate for the costs for the water management works that are a result from subsidence induced by gas production. Therefore, since the start of the production, subsidence is monitored with great care.
From the beginning leveling networks have been measured, connected to stable underground benchmarks outside the subsidence area. At first these surveys took place every three years. Since 1980, a course grid of about 750 km of leveling lines is surveyed on a yearly basis, and every 6 years, a more extensive network of 1600 km of leveling lines is measured. In time the area of subsidence has grown wider and newer adjacent fields were taken into production. As a consequence the size of the networks changed accordingly, the original stable benchmarks came under the influence of the subsidence bowl and new benchmarks,

GPS height measurements will rather supplement than replace leveling surveys for monitoring land subsidence further away, were established as connection points.

The GPS Campaigns

After some initial experimenting GPS campaigns were organized in spring and/or summer of 1994, 1995, 1996 and 1997. Since the main concern was the accuracy of GPS for height determination the NAM has taken great care in the design of the networks. Analyzing both precision and reliability the design criteria were:

- maximum distance between stations of 15 km;
- each station has to be occupied at least twice by different receivers;
- baselines along the perimeter of the network have to be measured at least twice;
- adequate siting in terms of obstructions, multipath, stability, accessibility and safety.

> *The Nederlandse Aardolie Maatschappij (NAM), has to compensate for the costs for the water management works that are a result from subsidence induced by gas production*

Since the leveling benchmarks, mostly bronze bolts cemented into walls of buildings, were unsuited for GPS measurements, separate GPS markers were established nearby a leveling benchmark. For the GPS networks an approach has been chosen involving a large number of short baselines. The main reason for this approach is that subsidence must be monitored over the whole area, involving many points. The length of the baselines is short enough to make use of the fact that the atmospheric delays above the stations are related, ambiguities are easy to find and observation times permit several occupations during normal working hours.

Processing of the GPS Measurements

The GPS data was first processed session by session using the Bernese GPS software. The sessions were then combined in a network adjustment using the Delft SCAN-3 software.
The processing with the Bernese software consisted of a free network solution for every session, using precise IGS orbits and resulted in a set of coordinates with their full covariance matrix. A standard troposphere model was used to correct for tropospheric delays. Ionospheric delays were taken care of by careful tuning of statistical input parameters. In addition, it was found that a 20 degrees elevation cutoff angle gave slightly better results than 15 degrees.
The results of the Bernese processing of sessions were subsequently subjected to a free network adjustment using the SCAN-3 software. The networks were designed to contain a considerable amount of redundancy with the objective to eliminate poor data and to analyze precision. The input for SCAN-3 is the set of coordinates for each session with their covariance matrix. A combination of hypothesis testing and variance component estimation was used in an iterative way to find the model that best fits the data.
Application of this procedure to the GPS campaigns resulted in a significant improvement up to 30% of the standard deviation of the height component.

Since large parts of the Netherlands, including Groningen, are situated below sea level surface, land subsidence has serious consequences for the water management systems in the area, making additional investments in sluices and pumping stations necessary. The producing oil company, the Nederlandse Aardolie Maatschappij (NAM), has to compensate for the costs for the water management works that are a result from subsidence induced by gas production.

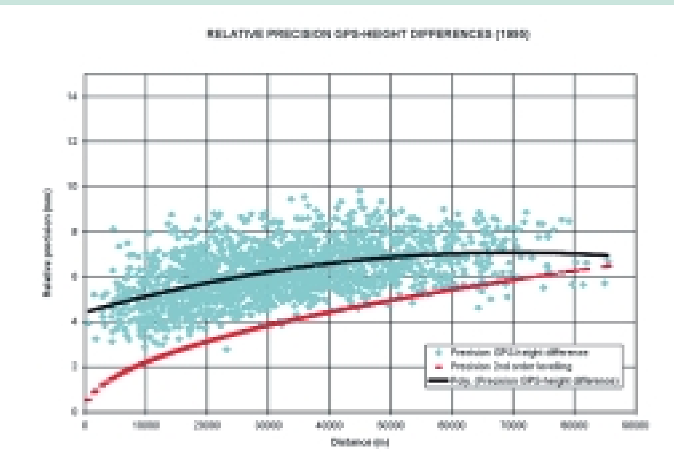

Figure 1: Relative precision of the height as function of the distance between points for GPS (1995 camign) and leveling

Conclusions

In figure 1 the relative precision in height is shown as function of the distance between points, for the four GPS networks and second order leveling (typical 0.7 mm/(km). The relative precision of the GPS heights is well below the one-centimeter level. After the networks were connected to common stable points, the difference in subsidence over a period of 3 years between GPS and leveling was computed. The RMS difference is about 5 mm/year. However, it must be realized that the precision of the GPS heights, despite the recent progress, is still less than the precision of conventional second order leveling. Therefore, GPS height measurements will rather supplement than replace leveling surveys for monitoring land subsidence.

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