GEODETIC WORK
IN
THE NETHERLANDS

1991-1994

Report prepared for the General Assembly of the
International Association of Geodesy, XXIth General Assembly of the
International Union of Geodesy and Geophysics
Boulder, 1995

NETHERLANDS GEODETIC COMMISSION

PUBLICATION OF THE NETHERLANDS GEODETIC COMMISSION

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Preface

It is with great pleasure that the Netherlands Geodetic Commission presents the National Report "Geodetic work in the Netherlands 1991-1994". Following the structure of the International Association of Geodesy, the National Report has been organized into the following five chapters:

1. Control surveys
2. Space techniques
3. Gravimetry and geoid
4. Theory and evaluation
5. Physical interpretation

Several scientists contributed to the National Report. Chapter 1 was written by H. van der Marel, with contributions from J. Denekamp, W. Groenewoud, S.W.P. Pulles and M.G. Vosselman. Chapter 2 was written by E.J.O. Schrama, with contributions from R.E. Molendijk, R. Noomen, R.T. Schillizi, P.G. Sluiter and P.J.G. Teunissen. Chapter 3 and 4 were written by respectively E. de Min and P.J.G. Teunissen. Chapter 5 was compiled by F.J.J. Brouwer, with contributions of W. Groenewoud and J.J.E. Pöttgens.

This report has been prepared for the General Assembly of the International Association of Geodesy, XXIth General Assembly of the International Union of Geodesy and Geophysics, to be held in Boulder, Colorado, USA 2 - 14 July 1995.

P.J.G. Teunissen
President of the Netherlands Geodetic Commission

Contents

1. Control surveys

The classical distinction between the horizontal and vertical component of geodesy, and land and water, has resulted in the Netherlands in a situation where different ministries are responsible for the various control survey activities. The three main geodetic reference systems in the Netherlands - for horizontal and vertical control and for gravity - are in the hands of two different authorities. The Triangulation Department of the Cadastre and Public Registers is responsible for the horizontal control network. The Survey Department of Rijkswaterstaat, Ministry of Transport, Public Works and Water Management, is responsible for the height control network and the gravimetric network. The space geodetic component is in the hands of the Faculty of Geodetic Engineering of the Delft University of Technology, which operates a satellite laser ranging and permanent GPS station at Kootwijk. Kootwijk is also one of the core stations of IGS. Finally, all activities concerning marine geodesy are handled by the Hydrographic Service of the Royal Netherlands Navy, Ministry of Defense, and the Survey Department of the Rijkswaterstaat.

All matters related to the national reference frames (horizontal-, vertical-, gravity and space) are coordinated by a special subcommission, named NEREF (NEtherlands REFerence frame), of the Netherlands Geodetic Commission (NCG), Royal Academy of Arts and Sciences. The marine geodetic activities are coordinated by the subcommission Marine Geodesy of the NCG. Finally, the Working Group for Applied Space Geodesy of the NCG is an important user group with representatives from university, government and industry. The working group publishes a newsbrief twice per year.

In the following paragraphs an overview is given of the control survey work in the Netherlands over the period 1991-1994.

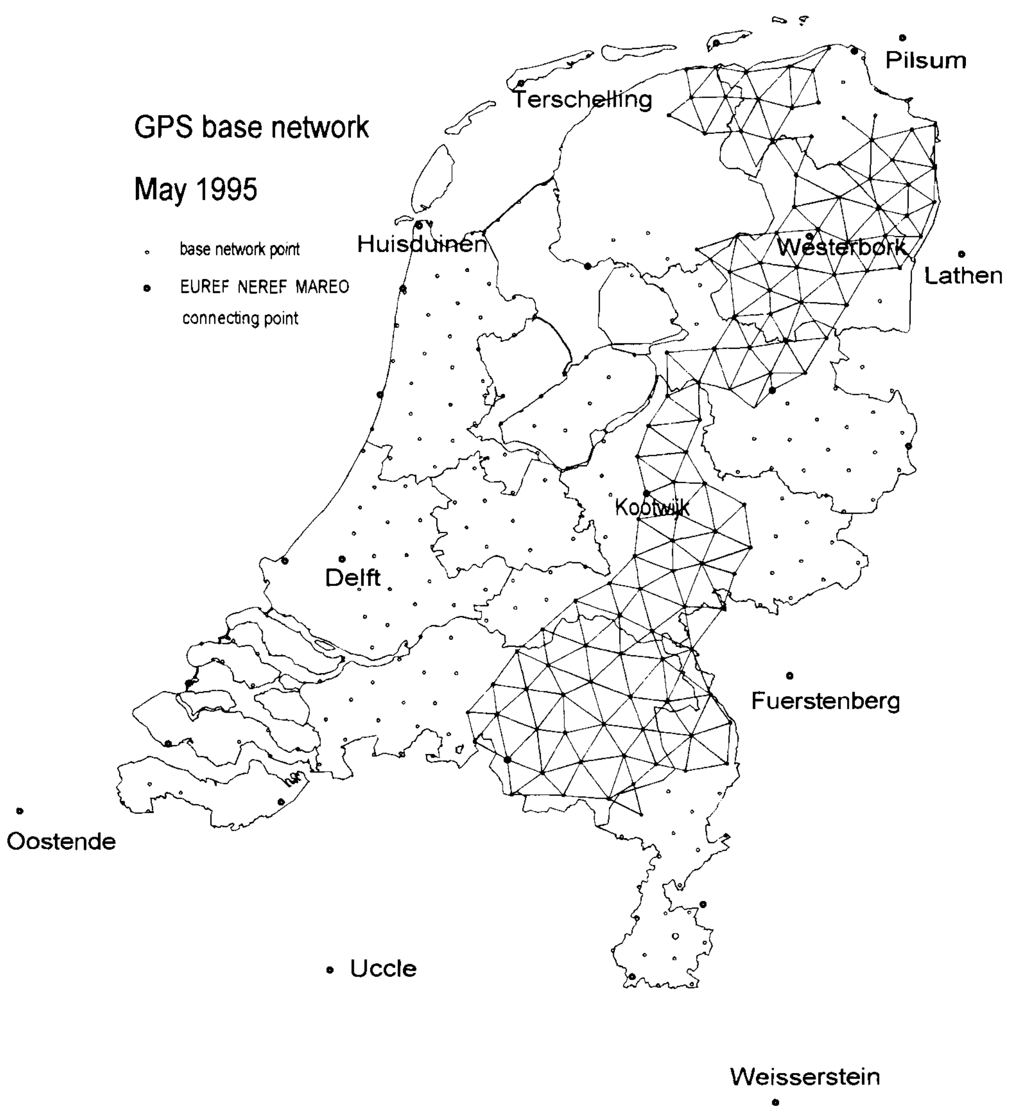
1.1 Horizontal control

The horizontal control network in the Netherlands, the so called Rijksdriehoeks system (RD-system), consists of about 6000 control points at an average distance of 2-3 km. Although the coordinates of these points are based on the first order triangulation network measured between 1885 and 1904, the quality of the reference frame is, even to today's standards, good enough for most surveying applications. The RD-system was, is, and will continue to be used, as the reference frame for almost all map production and the registration of real estate in the Netherlands.

Although the quality of the RD-system is sufficient for most GPS applications, many of the RD points are not very practical for GPS observations. Therefore, the Triangulation Department of the Cadastre and Public Registers started in 1991 to introduce 400 new RD-points, the so called *GPS base network* points. Two sets of coordinates will be published for the GPS base network points: one set in the national triangulation- and height system (RD/NAP), the other set in the European reference system ETRS'89. The GPS base network is therefore connected to the European Reference Frame. The relative distances between the GPS base network points are 10-15 km, making it possible for the user to use single frequency GPS receivers and modern fast (rapid static) GPS techniques for point positioning [Van Buren, 1993].

1.1.1 European Reference Frame (EUREF)

The IAG subcommission for the European Reference Frame (EUREF) has defined a reference system that is attached to the stable part of the European continent. Realizations of this reference system (ETRS'89) in the form of EUREF points with coordinates in ETRS'89 have become available in all European countries with accuracies of a few centimeters or better. In addition, parameters were determined which allow the transformation of coordinates from the European into the IERS system as well as into WGS-84.



Status of the GPS Base Network points with ties to the RD/NAP (points) and the status of the three-dimensional GPS base network (lines).

There are four EUREF points in the Netherlands, and six more EUREF points can be found not further away than 60 km from the Dutch borders. The distances between these EUREF points vary between 100-150 km. The EUREF points have been observed initially during the EUREF-89 GPS campaign. The Dutch and German points have been re-observed in May 1993 during the EUREF-D/NL-1993 GPS campaign. The data of the last campaign has been processed by IfAG, Leipzig. The results indicate a precision of better than 1 cm. This is confirmed by an analysis carried out at the Delft Geodetic Computing Centre using the newly developed SCAN-3 software [De Laat & van der Marel, 1994].

1.1.2 Netherlands Reference Frame (NEREF)

The number of EUREF points in the Netherlands is not enough to compute for instance reliable parameters for the transformation from the national coordinate system into ETRS'89, or to connect the GPS base network points to the European system. Therefore, the EUREF network has been densified, resulting in so called NEREF and MAREO points. During a first GPS campaign, the so called NEREF/MAREO 1990 campaign, mainly tide-gauges (MAREO points), were connected to EUREF. One year later, during the so called NEREF 1991 campaign, nine NEREF points have been connected to EUREF. Three of the NEREF points also have been measured during the NEREF-MAREO 1990 campaign.

The main distinction between NEREF and MAREO points is that the NEREF points also have good RD-coordinates. All NEREF points have been connected to first order triangulation points. On the other hand, the MAREO points are connected to underground levelling benchmarks and tide-gauge stations. Therefore, the nine NEREF and four EUREF points, for which we now have both EUREF and RD/NAP coordinates, have been used to compute an accurate national 7-parameter transformation and will be used to connect the GPS base network to ETRS'89. The MAREO points have their own role in the monitoring of tide-gauge stations. Since, both types of points have heights in the national (NAP) and European (EUREF) system, they will both contribute to the geoid computation [Brouwer et al. ,1993].

At present the NEREF 1991 and NEREF-MAREO 1990 campaigns are re-processed using the EUREF-D/NL-1993 coordinates instead of the EUREF'89 coordinates. In this way we hope to get a better precision. Since the two campaigns in 1990 and 1991 receiver technology has improved, more satellites, better orbits (IGS) and newly determined EUREF coordinates are available. Therefore, a new GPS campaign to re-observe the NEREF and MAREO sites was organized in October 1994. Results are expected in 1995.

1.1.3 GPS Base Network

The GPS base network will consist of about 437 points in the Netherlands with an average distance of 10-15 km. The purpose of this network is to make it possible to effectively use the national reference system in combination with GPS measurements, without the help of eccentric stations and without loss of quality. The points of the GPS base network are created when and where they are needed, and are connected almost immediately to the national reference frame by GPS measurements and levelling. At the end of 1994 340 of the planned 437 points were realized (see figure).

Each GPS base network point is connected to three or four surrounding RD points by GPS measurements. Occasionally an existing RD point may be suitable for and accepted as a point of the GPS base network. The distances to the surrounding RD points is not more than 5 km. Levelling between the GPS base network point and NAP benchmarks finally gives the orthometric height of the GPS base network point.

The points of the GPS base network are also interconnected by high precision GPS measurements to form the actual three-dimensional base network (see figure). This network will be connected to EUREF via NEREF once the full network has been measured. The new reference frame, based on EUREF, is *not* going to replace the old system. It will be used as an additional reference frame, to determine (locally) accurate transformation parameters between the national and European reference frames, and to assist the gravimetric geoid computation [Van der Marel et al., 1994]. Some of the characteristics of this network are: precision better than 1 cm (horizontal) and 1.5 cm (vertical), minimal detectable errors in the measured baselines smaller than 3 cm [Odijk, 1994].

1.1.4 GPS in the Netherlands

At the end of 1994 many government agencies and private firms are using GPS for their survey activities. The presence of GPS base network points has proved to be an important factor in the process of changing from traditional techniques to GPS.

The small distance between GPS base network points (10-15 km) allows users to use single frequency receivers to survey new points. More important, distances of 10-15 km to the nearest GPS base network points are ideal for "rapid-static" or "fast-static" methods, especially, if a modern dual-frequency receiver is available. These techniques result in a drastic reduction of the necessary observation time.

In almost all observation scenarios one of the receivers is set up as a, continuously observing, reference receiver for the duration of a measurement period. The other receivers then visit the new points, and, also some GPS base network points. If "rapid-static" or "fast-static" techniques are used the observation time per station can be limited to approximately 10 minutes. It is not necessary for the reference receiver to be on a GPS base network point. Other, possibly unmanned, locations also do. Although one GPS base network point is sufficient to determine the positions of the new points, two or three GPS base network points improve the reliability of the network. The GPS vectors can be transformed in the RD/NAP system with the help of previously determined transformation parameters and geoid model [Schut, 1991, 1992]. However, if the measurements are connected to three or more GPS base network points the user may also estimate his own transformation parameters.

In order to investigate the effect of Anti-Spoofing, which was switched on since January 31th 1994, the Working Group for Applied Satellite Geodesy of the Netherlands Commission for Geodesy, has organized a campaign to compare the accuracies of four geodetic GPS receivers [Sluiter et al., 1994]. This campaign was very successful and final results will be available early 1995.

1.1.5 Plans for an Active GPS Reference System

In 1993 the Faculty of Geodetic Engineering of the Delft University of Technology has initiated a design study for an Active GPS Reference System for the Netherlands. The Active GPS Reference system consists of a number of permanent GPS reference stations and a computing centre. Data will be collected in real time at the computing centre, and be processed and distributed to users in the country [De Jong et al., 1994]. In 1994 a prototype of a reference station with in house developed integrity monitoring software has been set up. Activities for 1995 will include the setup of a computing centre and more reference stations. The Survey Department of Rijkswaterstaat, the Cadastre and the Netherlands Geodetic Commission participate in this project since the end of 1994.

1.2 Vertical control

The Dutch height network consists of approximately 46000 benchmarks. The heights of these benchmarks are given as orthometric heights with respect to the national height datum NAP (Normaal Amsterdams Peil). The fundamental benchmark is located in Amsterdam. The NAP is also the origin of the United European Levelling Network UELN.
The backbone of the NAP is formed by a network of about 300 underground benchmarks, which have been placed since the start of the 2nd Primary Levelling (1926-1940) in the upper reaches of the Pleistocene sands. All underground benchmarks have fixed heights.
In the past, four Primary Levellings have been conveyed in the Netherlands: The 1st (1875-1895), 2nd (1926-1940), 3rd (1950-1959) and 4th (1965-1978) Primary Levellings. After the 4th Primary Levellings no new primary levelling was foreseen, since secondary levellings yielded (due to the higher density and redundancy of the measurements) almost the same precision for the heights of the benchmarks.

However, in the beginning of the 90's it was shown that the Pleistocene subsoil in the Netherlands is less stable that originally presumed. Also the NAP underground benchmarks (with fixed heights) are influenced by these vertical movements. A more or less instantaneous control of the network of underground benchmarks was needed in order to registrate and evaluate the (small) vertical deformations that have occurred in the NAP system over the years.
For this purpose a new Primary Levelling will be carried out in 1996-1997. The preparations for this 5th Primary levelling started in 1993. New aspects are the very short time span (compared to the previous Primary Levellings) in which the measurements will be carried out, the application of automatic optical and automatic hydrostatic levelling techniques, and the simultaneous conduction of GPS-measurements and gravimetric measurements at the underground benchmarks.

1.3 Marine-geodetic activities

1.3.1 The Netherlands

Hydrographic surveys were carried out in shipping lanes, deep draught routes and coastal areas, using traditional echosounders. Horizontal control was provided by a 2 MHz hyperbolic radio positioning system, which still acts as the primary positioning system. Since 1992 the survey vessels are equiped with differential GPS as secondary system.

The Hyperfix Thames Chain, which is jointly operated with the UK Navy, has been calibrated in 1992.

1.3.2 Continental Shelf Activities

On behalf of the Ministry of Economic Affairs checks were carried out on positioning data of offshore mining installations and on boundary and area computations.

1.3.3 General

The Hydrographic Service started developing software routines concerning Kalman Filter and DIA concepts (Detection, Identification and Adaptation). The implementation of these routines in the on board navigation/logging software is intended.
Various other software development was carried out, like coordinate transformations, area computations and GPS predictions.

1.4 Publications

1.4.1 Control surveys

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1.4.2 Vertical control

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1.4.3 Marine-geodesy

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2. Space techniques

2.1 Introduction

Delft University of Technology (DUT) hosts three different groups that are involved in the application of space techniques for geodetic purposes. These three groups are the section Fysische Meetkundige en Ruimtegeodesie (FMR) and the section Mathematical Geodesy and Positioning (MGP), both of the Faculty of Geodetic Engineering, and the section Space Research & Technology (SSR&T) of the Faculty of Aerospace Engineering. The Faculty of Geodetic Engineering also operates the Kootwijk Observatory for Satellite Geodesy (KOSG). Traditionally, the groups employ Satellite Laser Range (SLR) observations to precisely model satellite orbits, the deformations of the crust of the earth, polar motion and thereby angular momentum exchange of earth rotation. Since a decade, the scope of the research has been widened and now also includes topics like gravity fields and ocean currents. The range of observation techniques has been expanded with the Global Positioning System (GPS), satellite radar altimetry, Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Precise Range and Range-rate Equipment (PRARE) and Very Long Baseline Interferometry (VLBI).

The research is funded by DUT, the Netherlands Organization for Scientific Research (NWO), Space Research Organization Netherlands (SRON), the Netherlands Remote Sensing Board (BCRS), the Survey Department (MD) of Rijkswaterstaat, the European Space Agency (ESA), the National Oceanographic and Atmospheric Administration (NOAA), the Netherlands Foundation for Research in Astronomy (NFRA) and the Royal Academy of Arts and Sciences (KNAW).

2.2 National and international cooperation

Most of the research is part of the following long-term international research projects:

Dynamics of the Solid Earth (DOSE): This project has three different research topics: (i) the deformations of the earth's crust and the rotation of the earth; (ii) the uplift phenomenon in Fennoscandia and Canada; and (iii) the relationships between height changes, sea-level changes and global warming. The contribution of DUT concerns tracking and analysis.

WEGENER-2 Project: This project is linked to the DOSE Project. Its goal is identical to that of DOSE, albeit that it is focused on the European situation. As such, it can be regarded as an extended follow-up for the WEGENER-MEDLAS Project. The contribution of DUT is primarily aimed at the detection of crustal deformations in Europe in general and in the central and eastern Mediterranean area in particular. This is effectuated by the deployment of SLR and GPS tracking equipment and the analysis of the data from various measurement campaign

International Earth Rotation Service (IERS): This project, which is executed under the auspices of the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG), aims primarily at the determination of the rotational motion of the earth with a high temporal resolution. Since 1988, DUT acts as one of the operational SLR data analysis centers, and produces weekly semi real-time solutions for the earth rotation parameters from quick-look SLR observations. In addition, high-precision earth rotation parameter solutions are computed once a year from full-rate SLR measurements.

LAGEOS-2: Traditionally, SLR activities from crustal dynamics investigations focus on the LAGEOS-1 satellite. Since October 1992, the space segment for this particular application has been doubled with the launch of LAGEOS-2, similar to LAGEOS-1 in design and many orbital characteristics. The LAGEOS-2 Project is led by NASA and the Italian Space Agency. In the analyses observations of LAGEOS-1 and LAGEOS-2 are combined, yielding more precise solutions for station positions and earth rotation parameters.

ERS-1: The ESA satellite ERS-1, launched in July 1991, is equipped with a radar altimeter, which allows the precise measurement of the distance between the satellite and the sea surface underneath. The altimeter observations are processed by DUT, in cooperation with the Institute of Meteorology and Oceanography (IMAU, Utrecht University), the Netherlands Institute for Sea Research (NIOZ), the Tidal Waters Division of Rijkswaterstaat (RIKZ) and the Koninklijk Nederlands Meteorologisch Instituut (KNMI). The research aims primarily at the computation of precise ERS-1 orbits, the modeling of the marine geoid and the measurement of large-scale ocean currents and waves.

TOPEX/Poseidon: Another altimeter satellite, TOPEX/Poseidon, was launched in August 1992. The Dutch team mentioned above is intensively involved in the analysis of the observations of this NASA/CNES satellite. The activities concern the precise computation of orbits (using SLR, GPS and DORIS observations), the study of ocean circulation and gravity field studies.

Gradiometry: DUT has been involved in the preparations for the ESA/NASA ARISTOTELES mission, a satellite dedicated to the study of the earth's gravity and magnetic fields. The team has focused in particular on the development of suitable techniques to process the large amount of gradiometer and spaceborne GPS observations, [17]. Rather similar is the Satellite Test of the Equivalence Principle (STEP) Project, which uses a future drag-compensated satellite to study the gravity field of the earth with unprecedented accuracy.

2.2.1 Tracking and orbit determination

The determination of precise satellite orbits from various types of tracking data is essential for each of the fields of interest mentioned above. DUT is already for a long time actively involved in several aspects of satellite tracking and orbit determination.

FMR operates the third-generation mobile SLR system MTLRS-2, which went through a series of upgrades during the last few years. The precise coordinates of the geodetic reference point at Kootwijk are maintained through regular observation campaigns with this system. Its function of a reference station is further enhanced by a Rogue GPS receiver purchased in 1989 whereby the turbo-rogue serves as a backup. Combined with observations taken at other global stations, both types of data are used to compute the orbits of SLR and GPS satellites, respectively. The important role of Kootwijk in this respect is recognized by its selection as one of the core stations for the International GPS Service for Geodynamics (IGS) network.

To further expand its role and to be able to observe ERS-2 and other future ESA satellites, a PRARE ground station undergoes testing procedures in Kootwijk since October 1994.

With the availability of a GPS receiver and a PRARE transponder at the laser site, KOSG offers the unique opportunity to tie the global networks of SLR, GPS and PRARE stations.

The tracking data acquired by global laser and radio-frequency tracking systems on the LAGEOS-1, LAGEOS-2, ERS-1, TOPEX/Poseidon and GPS satellites are processed by SSR&T to determine very accurate orbits for these satellites, compare for instance [21] and [22]. Here, various model parameters are solved for simultaneously, resulting in an improved quality of the orbit solution. The parameter solutions themselves may also give interesting geodetic and geophysical information: SLR and GPS measurements provide precise solutions for the epoch coordinates and their time-derivatives of geodetic reference points and (SLR only) earth rotation parameters.

For ERS-1 and TOPEX/Poseidon, new techniques have been developed to determine very accurate orbits. The combination of SLR and radio-frequency measurements results in the highest orbit accuracy, which is an absolute requirement for satellite altimetry.

2.2.2 Working Group for Applied Space Geodesy

The Netherlands Geodetic Commission has a Working Group for Applied Space Geodesy, wherein universities, government agencies and industry are represented. An important objective of this group is to stimulate interaction in GPS matters. Activities of this group are: 1) Publication of the twice-yearly newsletter "GPS-Nieuwsbrief", with articles in English and Dutch, 2) Presentations for geodetic professional associations and articles in their journals. 3) Post-graduate courses in GPS. Furthermore a research project has been executed to compare the capabilities of four dual-frequency GPS receivers under Anti-Spoofing conditions. Specific attention has been given to the following aspects: 1) survey of a 100 km baseline, using observed ionospheric corrections, 2) survey of a 10 km baseline in rapid static mode using the observations on two frequencies, but without an ionospheric correction, 3) susceptibility to Radio Frequency Interference (RFI), both in uncontrolled operational conditions and by generating jamming signals at controlled power levels, 4) noise in the various observables.

2.2.3 Very Long Baseline Interferometry

During the period under review, work in geodetic VLBI was carried out at the Netherlands Foundation for Research in Astronomy (NFRA) and the Survey Department of Rijkswaterstaat (RWS/MD) where it has been integrated in a research program on monitoring land subsidence and sea level change.

Since the Westerbork Synthesis Radio Telescope (WSRT) is not equipped with S/X receivers, it has not participated in geodetic VLBI campaigns since 1987. Therefore, time has mainly been spent on computational methods for geodetic VLBI (upgrading of the DEGRIAS software) and research on the applicability of a VLBI radiotelescope in space.

To stay in touch with activities in the field of geodetic VLBI, RWS/MD has continued its participation in the European Working Group for Geodetic and Astrometric VLBI. In June 1991 the 8th Working Meeting on European VLBI for Geodesy and Astrometry was organized by RWS/MD and NFRA in the Netherlands, [2].

In addition, RWS/MD is participating with six other institutes in an EU SCIENCE project 'European Geodetic VLBI for Crustal Dynamics'. Scientific objectives are a better understanding of tectonic movements in the western Mediterranean and, as far as possible, identification and investigation of areas of uplift and subsidence in Europe.

In 1992 the European VLBI community received funding for an upgrade of the European VLBI Network (EVN). A (new) supporting center (Joint Institute for VLBI in Europe - JIVE), located in Dwingeloo, is coordinating the construction of a new 16 station correlator primarily for astronomy and astrometry but with time available for geodesy as well if needed. The WSRT will also acquire S/X receivers for all 14 elements of the array in 1998, so that it will be able to participate in (European) geodetic VLBI campaigns.

2.2.4 Crustal dynamics

The activities of DUT concerning crustal dynamics studies during the period reported here can be divided into WEGENER-MEDLAS and WEGENER-GPS (epoch'92). The analyses performed under WEGENER are based on SLR observations taken by the global network of laser stations and GPS observations taken by a European network of stations. The research aims in particular at the determination of crustal deformations in the central and eastern Mediterranean area, which is the meeting place of three major tectonic plates: Eurasia, Africa and Arabia, [14] [15] [28].

The SLR component of the analyses, WEGENER-MEDLAS, relies on the observations taken by the mobile systems deployed at some 15 sites in the area during several dedicated measurement campaigns. In 1992, during the reporting period, the fourth observational campaign took place, with participation from our mobile SLR system MTLRS-2. The measurements taken during this campaign have provided very valuable observational evidence of the crustal deformations taking place in this region. The same holds for the two GPS campaigns WEGENER-GPS (epoch'92), which were analyzed during the reporting period.

Also, DUT has continued its role as Quick-Look Data Analysis Center (QLDAC) of the WEGENER Project. The purpose of this activity is threefold: (i) SLR data quality control on a semi real-time basis; (ii) computation (observation) of earth rotation parameters; and (iii) monitoring of the data yield of mobile tracking instruments during observation campaigns, to minimize the deployment periods and to maximize the output of such a campaign. Since its launch in late 1992, QLDAC processes observations of LAGEOS-1 and LAGEOS-2 simultaneously, [15].

WEGENER/GPS-92 took place from July 29 until August 3, 1992, during the (epoch'92) campaign, [29]. Carried out under the leadership of the Institut für Angewandte Geodäsie (IfAG) in Frankfurt, a network of European stations was observed with state-of-the-art geodetic GPS tracking equipment. The exact positions of most of these sites are also observed using SLR and/or VLBI techniques. This not only allowed a mutual benchmark of basically different techniques, but also provided an additional epoch observation of the relative positions of the stations in the network. Although problems have been identified at a few stations, this GPS campaign has proven to supply a very valuable contribution to crustal dynamics studies in the area.

The same conclusion applies to EUREF-89, a GPS campaign which took place from May 16 to May 28, 1989. The horizontal components of the position solutions obtained from this campaign provided very valuable for the proper determination and understanding of deformations in southeast Europe, [16].

The analysis of the measurements taken during the four SLR campaigns (earlier ones took place in 1986, 1987 and 1989) and during the two GPS campaigns has resulted in a very clear picture of the tectonics of southeast Europe. The results unmistakably show the counterclockwise rotation of Anatolia and the southwestward motion of central and southern Greece. Sites in the Italian part of the network, however, show a very small northward motion, which may be correlated with Africa motion. Motion vector solutions for stations in Egypt, Israel and Turkey show a good agreement with unperturbed motion of Africa and Arabia, respectively, [10] [15].

In 1994, a third dedicated GPS campaign for the observation of epoch positions of the WEGENER monuments was carried out: WEGENER/GPS-94. Also, two mobile SLR systems visited several sites in the region during this year. The data taken during each of the campaigns has not been analyzed yet, but are expected to more accurately characterize the crustal deformations in the area. This holds in particular true, since these measurements were obtained two years after the last observation campaigns (1992, both with SLR and GPS).

2.3 Kootwijk Observatory for Satellite Geodesy (KOSG)

2.3.1 Operations

MTLRS-2: In 1991 MTLRS-2 occupied Monte Venda (Italy) where radio frequency interference test measurement were conducted. Moreover MTLRS-2 participated in an observation campaign to calibrate the ERS-1 altimeter launched on July 17 1991. In 1992 the transportable laser system MTLRS-2 participated in the WEGENER-MEDLAS campaign and has been deployed in Greece from March. Data acquisition was significantly low and this could not be sufficiently cured by intensive trouble shooting in field conditions. In August 1992 the system was called back to Kootwijk for further inspection. Although all in all sufficient data has been collected at the Dionysos site, the remainder of the observation schedule for the system in Greece and Italy could not be completed.

IGS station: The ROGUE SNR-8 GPS receiver performed without significant problems and the loss of data was less than 1%. The data has been submitted daily to the NASA crustal dynamics data information system in view of the participation in the International GPS Geodynamics Service (IGS). After the experimental stage of the IGS since 1991, the service now has taken a permanent status, primarily focusing on determination of earth rotation and of GPS orbits, as well as to support global reference system definition. In the now permanent service, KOSG has been selected as one of 13 stations in the fiducial network, for routine global analysis by all IGS analysis centers.

Transportable GPS: Two turbo Rogue SNR-8000 GPS receivers have been extensively tested and are fully operational. Test measurements have been performed to prepare future replacement of the permanent receiver in the Kootwijk IGS station and in view of the development of an Active GPS Reference System (AGRS) in the Netherlands. Both receivers have been deployed in three campaigns in the Netherlands to investigate the stability of the surge barrier in the Oosterschelde.

2.3.2 Instrument development MTLRS-1/2 and TIGO

Various parts of the MTLRS-1 and 2 systems were renewed in the period covered by this report. First, a new pulse laser has been implemented in MTLRS-2 performing successfully according to the specifications. Second, the central processor board, hosting the T805 transputer and most of the other PC boards were renewed and a remote control unit for the field of view setting was implemented; the new control systems were tested for MTLRS-1 and 2 as from summer 1994. Third, a new start detector (avalanche diode) has been implemented in MTLRS-2. Fourth, the Product Centrum TNO assisted in maintenance and inspection of the mechanical and optical sub-systems; test measurements during the summer of 1993 indicated that these sub-systems had regained their nominal acquisition level.

Jointly with TPD/TNO, a contract has been signed with the Institut für Angewandte Geodäsie (IfAG) for the delivery of a new, state-of-the-art satellite laser ranging system, as one of the major components of the Transportable Integrated Geodetic Observatory (TIGO). KOSG is responsible for the delivery (in 1995) of the controller sub-system. These activities considerably overlapped the work on the MTLRS control systems. Most of the design aspects have been worked at and discussed with TPD/TNO and the IfAG.

2.4 Earth rotation

Since 1988, SSR&T determines earth rotation parameters from SLR data of LAGEOS-1 on a continuous basis. These parameters are transmitted weekly to the IERS Project of the IAU and the IUGG. These solutions are combined by IERS with results obtained by similar and other measurement techniques to yield the most accurate observation of the actual rotational motion of the earth. Prior to October 1992, the solutions were based on LAGEOS-1 data only. Since then, LAGEOS-2 observations are being processed simultaneously with LAGEOS-1 data. The combination of these two satellites has allowed an increment of the temporal resolution of the solutions to once per three days.

In addition, the computation of the earth rotation parameters is repeated with the final, fully corrected version of the SLR observations once a year, yielding the most accurate solutions achievable today. As an ongoing activity, DUT is studying the mechanisms and physical processes which affect earth rotation.

2.5 Gravity field

2.5.1 Introduction

The proper understanding and modeling of the gravity field of the earth is essential for the computation of precise satellite orbits and the study of a wide variety of geodetic and geophysical phenomena. During the reporting period, DUT has performed studies on the determination of the gravity field from gradiometry and from observed perturbations in the orbit of satellites, [30] [37] [38].

2.5.2 Theoretical developments

The time-like approach to gravitational field modeling from space observables is based upon a spectral representation of satellite orbit perturbations and other functionals of the gravitational potential measured at satellite altitude. The general framework for this theory was further developed and improved. A very efficient description is possible in terms of so-called lumped coefficients and using complex notation. This general frame-work can be used for gravitational field (error) analysis from first as well as second-order gravitational potential derivatives as they are observable from satellite-to-satellite tracking, e.g. by means of spaceborne GPS, and satellite gradiometry. Under certain assumptions it is possible to use this theory for very detailed gravitational field analysis without much computational effort, [9] [18] [19] [22a] [26] [30] [31] [35].

2.5.3 Software

Since no actual gradiometric satellite mission has ever flown yet, a full analysis with real data is not possible. One has to use simulated data in order to investigate the problems related to estimation of potential coefficients from gradiometric observations. A first preparatory analysis of 1 month simulated gradient data was performed, both by using a time-like as well as a space-like approach. Furthermore, a software package for orbit and gradiometric synthesis and analysis is under development. Detailed gravity field analysis puts high demands on the software and computational improvements are necessary. Several steps in the analysis scheme were improved by using numerical techniques. The analysis includes an iterative solution procedure where in each step the whole process should be repeated. Emphasis was put on the influence of polar gaps, aliasing and measurement error on global gravity field recovery.

2.6 Satellite altimetry

DUT is heavily involved in the processing of observations of radar altimetry satellites: GEOSAT, ERS-1 and TOPEX/Poseidon. Basically, the activities can be divided into: orbit computations, the marine gravity field and deep ocean tides models, and oceanographic studies, [20] [39].

2.6.1 Orbit computations

The precise computation of the orbits of altimeter satellites is difficult for a number of reasons. First, they encircle the earth at relatively low altitudes introducing perturbing accelerations caused by the earth's gravity field, tides and atmospheric forces. Second, the shape of the spacecraft is mostly irregular, which complicates the correct modeling of the tiny but essential surface forces. Third, the amount of observations acquired by traditional tracking stations is relatively small, which weakens the quality of the orbital solutions although it should be remarked that DORIS, PRARE and GPS change this situation, [22].

Refined models for surface forces and a detailed assessment of the attitude behavior of T/P and ERS-1 are incorporated in the orbit computation software of the DUT altimeter team. As a result, it was possible to determine the orbit of TOPEX/Poseidon with an unprecedented precision of about 3 cm in the radial direction (for ERS-1, this value amounts to approximately 13 cm). The results obtained for TOPEX/Poseidon are better than the specifications in the mission design requirements, [14]

2.6.2 Marine gravity field and tides

Various research projects focussed on these topics: First, Geosat Exact Repeat Mission data has been used to study the correlation between bathymetry, i.e. the sea floor topography, and its isostatic compensation according to the Airy-Heiskanen model, [1]. Second, along-track second-order derivatives are combined using Laplace's equation to obtain vertical gravity gradients, [19a]. The final results clearly show correlation with geological features in the Barents Sea. Third, A theoretical study was performed to clarify the nature of various definitions of the so-called geographically correlated orbit error. It is shown that this error should have a long wavelength character, see also [20] and [23]. Fourth, By using 2 years of T/P altimeter data a preliminary deep ocean tide model has been developed. In a ground truth verification test it was noticed that this new model outperforms all previously released deep ocean tide models, see also [24].

2.6.3 Oceanography and altimetry

In the period covered by this report several altimeter studies focussed on the relation to physical oceanography. First, the low degree and order spherical harmonic expansion of the mean dynamic topography can be modeled by a comparison of the mean altimeter surface to a geoid model, compare [5] [7] [8] [14] [32] [34]. Second, sea level variability can be computed in various ways. A commonly applied procedure is to focus on the difference in observed altimeter heights with respect to a long term mean, compare [3] [4] [5] [11].

2.7 GPS positioning and navigation

2.7.1 Development of an experimental Active GPS Reference System in the Netherlands

On the basis of a proposal by prof. Teunissen a start was made in 1994 with the development of an experimental Active GPS Reference System in the Netherlands [1-5]. The development is a collaborative effort of DUT, MD-RWS, the Cadastre and the Netherlands Geodetic Commission. Such an Active GPS Reference System (AGRS) will contribute to a wide variety of scientific and practical applications, as can be seen from the following table.

Scientific	Practical
- Monitoring GPS - Monitoring sea level rise - Monitoring land subsidence - Global and regional orbit determination - Atmospheric modelling	- Real-time navigation - Real-time positioning for Geographic Information Systems - Land surveying

The experimental AGRS will consist of the following components:

- One Centre for Processing, Storage and Distribution of data (CPSD)
- Five reference stations
- One monitoring station
- Two operator terminals

The reference stations permanently collect data from all visible satellites. In addition they also collect meteorological data. Immediately after the data has been collected and validated by the integrity monitoring software, it is transmitted to the CPSD. At the CPSD, the data is processed and stored. Processing consists of real-time validation of the network of reference stations, determination of orbital corrections, differential corrections for real-time positioning applications and ionospheric model parameters. Original data and processing results are made available to users by means of a data retrieval system. For non-real-time applications, data will be available with a delay of less than 30 minutes. A monitoring station is very similar to a reference station, the only difference being the lack of a communication link with the CPSD for data transmission.

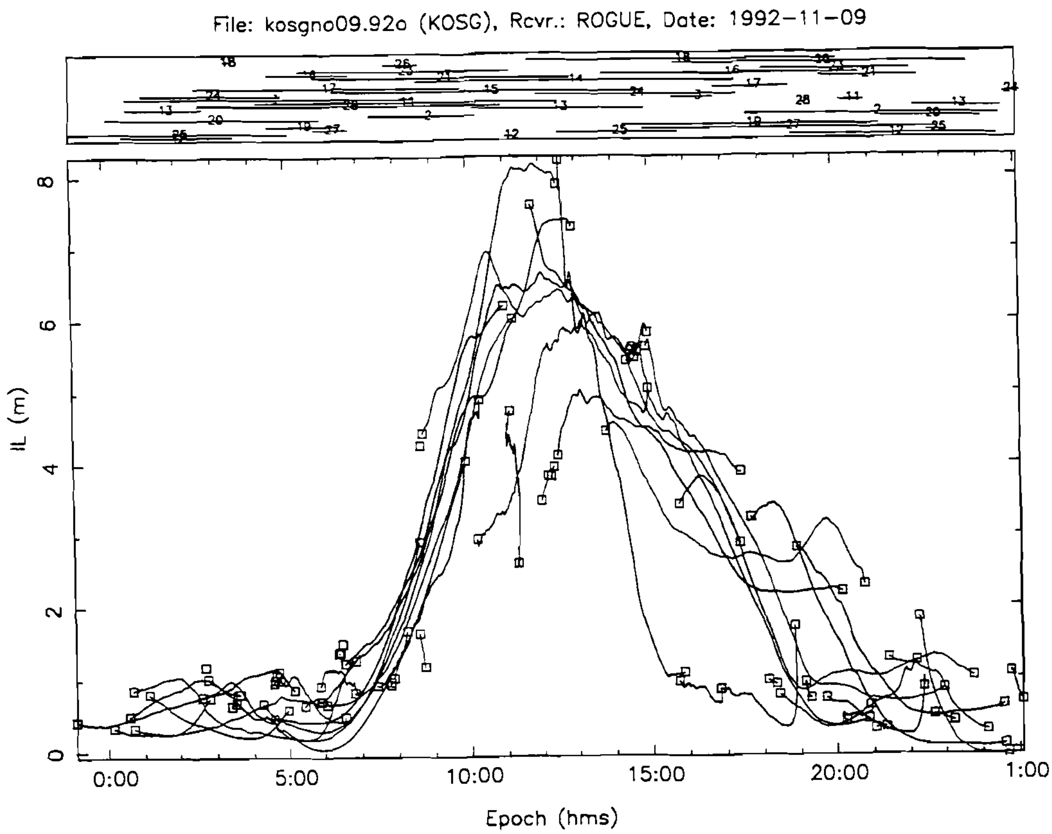
It can be used for stand-alone monitoring of GPS or for both GPS and AGRS. In the latter case, it will obtain data from the CPSD's data retrieval system.

The CPSD and the reference and monitoring stations are unmanned. They are equipped with communications soft- and hardware, which allows for remote operation by means of an operator terminal, which consist of a computer, modem and communications software. In case of an alarm (generated e.g. because the receiver is not tracking satellites, or because the CPSD's link with a reference station could not be maintained), the integrity monitoring software will alert the operator, who, using his operator terminal, can access the facility which generated the alarm and take appropriate action.

For an Active GPS Reference System (AGRS), even in its experimental stage, data management will be a very important issue. With a number of reference stations continuously tracking all visible satellites, the amount of collected data will be very large. This research project focuses on the development of efficient formats for transmitting data from the reference stations to the AGRS' Centre for Processing, Storage and Distribution (CPSD), and for storing and retrieving it.

2.7.2 Real-time integrity monitoring of GPS data

For the reference stations of the AGRS, but also for stand-alone monitoring and mobile stations, it is very important to monitor the quality of the collected GPS data. Especially for real-time applications, which become increasingly important, the integrity monitoring should preferably be based on data from a single receiver. Two software packages have been developed for this purpose, one for dual-frequency, the other for single-frequency GPS data. The integrity monitoring is based on the DIA-theory, developed at the Delft Geodetic Computing Centre. Interfaces are available for two popular GPS receivers, the TurboRogue SNR8000/SNR8100 and the Trimble 4000SSE. It is also possible to process previously collected data. The software was developed not only for DUT's own purpo-



Vertical ionospheric delay (in meters) at 1546 MHz versus local time of the sub-ionospheric point extracted from Rogue data collected at Kootwijk observatory (9 November 1993).

ses, but also for the Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR) in Neustrelitz, Germany.

2.7.3 Local and regional ionospheric modelling

Dual frequency GPS observations yield valuable information about the ionosphere in the direction of the satellite. This information can be of great use within various GPS applications and in the context of the AGRS, but it is also useful for other applications, e.g. for the correction of observations done by the radio telescope in Westerbork. In 1993 a start was made with the development of software for the monitoring of the ionosphere using a single GPS receiver. The determinations of ionospheric TEC's have been compared to chirpsounder and ionosonde measurements. This model will be further enhanced to deal with specific instrumental delays and to function in a network of GPS receivers [6, 7].

2.7.4 GPS and hydrography

On request of the Survey Department of Rijkswaterstaat the feasibility of using GPS for accurate height determination of the echosounder transducer in bathymetric applications was investigated. Extensive experiments to test the dynamic GPS relative positioning performance have shown that vertical decimeter accuracy for baselines of a few tens of kilometers is achievable under operational conditions. For the purpose of laboratory tests, a wave simulator has been developed [8].

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2.8.1 National and international cooperation, Gravity field, Satellite altimetry

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3. Gravimetry and geoid

3.1 Introduction and history

In 1989 the Survey Department of Rijkswaterstaat and the Faculty of Geodetic Engineering of the Delft University of Technology decided to start a geoid project for the Netherlands. The goal of this project is to obtain the best possible geoid, aiming at cm precision for relative geoid heights. This precision is needed to be able to compute orthometric height differences from GPS measurements. The last geoid for the Netherlands was computed by Van Willigen in 1985 (Van Willigen, 1985), and has a precision of 10 cm over 100 km, which is not enough for this new application. The available gravity data in the Netherlands area consisted only of a 1:600,000 Bouguer anomaly map. The measurements which are the basis of this map, and which were done in the 1940-1950's, were not available anymore. Using height information and digitizing the Bouguer map, 3'x5' (5.5x5.5 km^2) mean block values were computed. However, the quality of these values was estimated to be $1\text{-}2 \cdot 10^{-5}$ ms^{-2}, with the possibility that systematic errors were present. Since no orthometric corrections are needed in the flat country of the Netherlands no second order gravity measurements were available. Therefore, it was decided to measure a completely new gravity network in the entire Netherlands.

This chapter describes the structure and results of this gravity network and the performed efforts in the geoid computation field. In 1995 the project will be finished and supplies the Netherlands with a geoid with relative precision of 1 cm.

3.2 Gravity project

The gravity network has been set up in four stages. Four absolute stations have been measured, fifty first order points and 8000 second order points on land. Besides these land measurements, gravity measurements have been done on the IJsselmeer and Waddenzee, which are innerwaters in the Netherlands. The complete network supplies us with a gravity field description in the Dutch area with the possibility to obtain cm geoid precision.

3.2.1 Absolute gravity measurements

In 1991 and 1993 absolute gravity measurements have been done on four stations in the Netherlands. All these measurements have been done by the Institut für Erdmessung of the Hannover University with their JILA-G3 instrument. In 1991 three stations have been visited, the VLBI station in Westerbork, the satellite observatory in Kootwijk and building of the Faculty of Geodetic Engineering in Delft (Van Ree, 1991). The station in Delft turned out to be unsuitable for absolute gravity measurements, due to the unstable underground close to the Northsea coast. In 1993 measurements have been done again in Kootwijk and at the seismic station in Epen. The difference at the Kootwijk station with respect to the 1991 value was $+17 \cdot 10^{-8}$ ms^{-2}. The station in Epen turned out to be one of the most stable ones in Europe, due to the foundation of this building on the Carboon. The results of all these absolute gravity measurements are reported in (Strang van Hees et al., 1995).

3.2.2 First order gravity network

The first order gravity network originally consisted of two parts. About twentyfive stations are located at underground benchmarks of Rijkswaterstaat, and twentyfive stations are located at national railway stations. An extensive analysis of all the relative gravity measurements from the period 1986-1993 has been made. For all fifty stations a final value has been computed using about 2170 measurements, and the absolute values described in the previous section and absolute values in Germany, just over the border with the Netherlands. These values form the Netherlands Gravity datum 1993 (De Min, 1994a). The precision of these first order values is $5 \cdot 10^{-8}$ ms^{-2}, the external reliability is $9 \cdot 10^{-8}$ ms^{-2}.

From this total adjustment, including all relative and absolute gravity measurements, it also turned out that the difference of the absolute values in Kootwijk in 1991 and 1993 is purely coincidental, and does not indicate a real gravity value change. Besides, the corrections which are applied to the two absolute values in this complete adjustment, respectively $+9 \cdot 10^{-8}$ ms^{-2} and $-8 \cdot 10^{-8}$ ms^{-2} are within the standard deviation margins of $10 \cdot 10^{-8}$ ms^{-2} .

3.2.3 Second order gravity network

In 1989 a test network has been measured in the south eastern part of the Netherlands (De Peel) by the Faculty of Geodetic Engineering to study the necessary density of the second order gravity network in order to obtain a cm geoid quality from the inner zone contribution (Nohlmans, 1990). It turned out that 1 point per 5 km^2 (point distance about 2 km) is very appropriate. The Survey Department has done about 13000 relative gravity measurements at 8000 stations in the period 1990-1994. All stations are located near height benchmarks of the NAP system. About 60% of the stations have been visited more than once. This is on the one hand been done to be able to compute gravimeter drift, and on the other hand to have a redundancy in measurements to find errors and to estimate the quality of the network. It was decided not to measure all stations at least twice because of financial reasons.

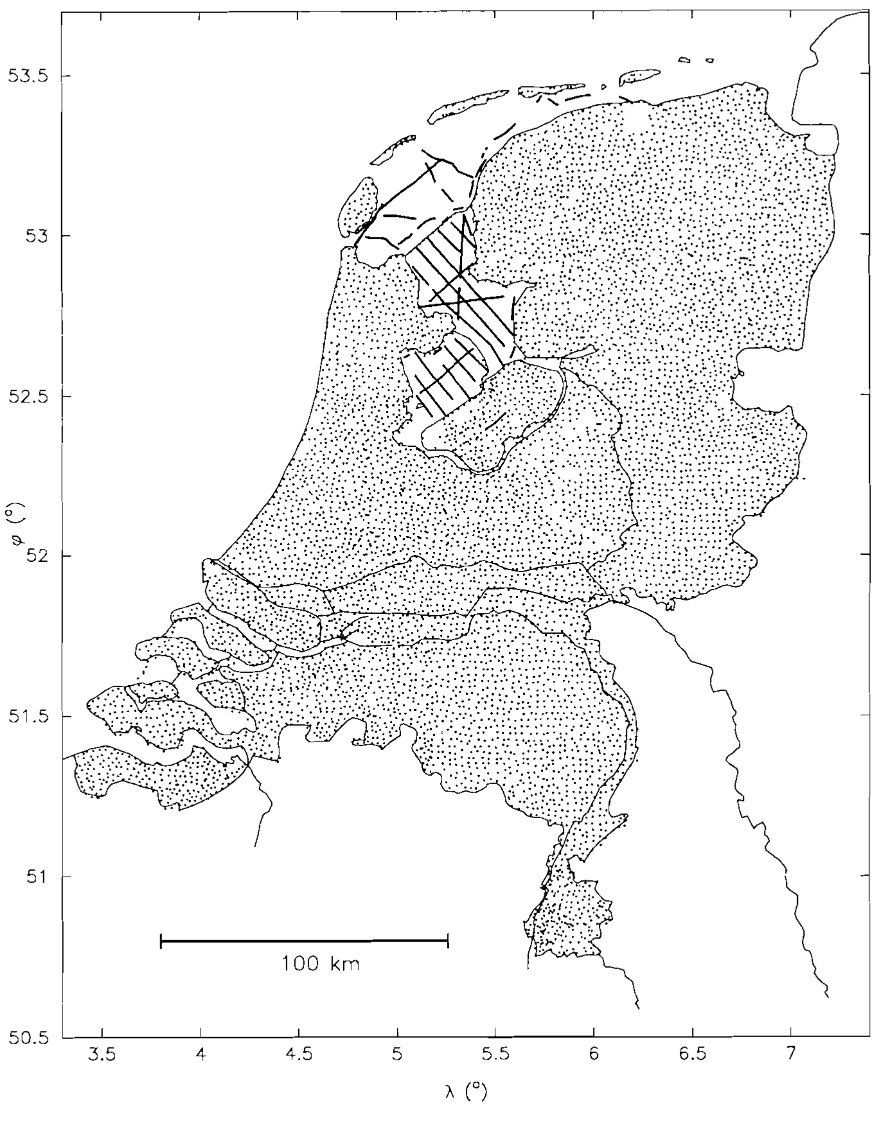
The adjustment of the second order network has been done by the Survey Department and the Faculty of Geodetic Engineering. First the small local networks were controled and adjusted to find possible errors. Then 10 networks of about 800 stations were created. In every of these 10 networks at least three first order stations were connected. Every two neighbouring networks had overlapping stations. The differences of these independently determined two or three values indicate that the precision of the second order values is between 30 to $100 \cdot 10^{-8}$ ms^{-2}.

In a final step for all second order stations a value has been predicted using least squares prediction using only neighbouring station values and not the station value itself. From a comparison of the formal error estimate of least squares prediction and the difference between measured value and predicted value reading errors, writing errors and typing errors of stations with only one measurement could be detected. If the difference is larger than twice the error estimate, or if the difference is larger than $1 \cdot 10^{-5}$ ms^{-2}, the measurements have been inspected again.

3.2.4 Sea gravimetry measurements

Because there is a large innerlake and innersea in the Netherlands, respectively IJsselmeer and Waddenzee, a sea gravimetry campaign has been organized. Nearly 3400 mean gravity values for 1 minute time intervals, which equals about 200 m, were computed. The precision of the sea gravimetry values is estimated to be $1{,}5\text{-}2 \cdot 10^{-5}$ ms^{-2} based on crossings of measurement profiles and connections to harbour stations (Weesie, 1993). Based on the harbour connections it is possible to increase the final precision of the sea gravimetry measurements. The figure below shows a picture with all measurement stations of the second order network on land and the sea gravimetry profiles.

In 1986 there has already been an sea gravimetry project in the Dutch part of the Northsea to obtain a fine gravity dataset for geoid computation.



All stations of the second order project on land and the Wadgrav project at sea.

3.3 Geoid project

For the most precise geoid computation for the Netherlands the exact method to be used has to be defined. Since the Netherlands is a very flat country at sea level there are no significant differences between orthometric and normal heights, and hence also not between geoid heights and quasi-geoid heights.

3.3.1 Available data

The gravimetric geoid will be computed using a global geopotential model upto degree and order 360, which is OSU91, and land- and sea gravimetry data upto 5 degrees from the Dutch area. This dataset upto 5 degrees from the geoid computation points consists of the mentioned new gravity dataset on land and on sea in and around the Netherlands. This dataset is completed with point data made available by Bureau Gravimétrique International, land gravity data and sea gravity data from the British Geological Service, and 6'x10' mean gravity anomalies.

3.3.2 Kernel modifications in combination solutions

Since the use of a modified kernel can optimize the use of these available datasets these kernel modifications have been studied. Because a correct error description of the inner zone gravity data in spectral error degree variances is hardly possible, only the deterministic kernel modifications are studied. Based on physical arguments one of these kernel modifications can be chosen. It was finally decided to use the combined Meissl/Wong&-Gore kernel modification, where the Stokes' function upto degree 22 has been subtracted for the inner zone computation. From tests is was shown that the results between different kernel modifications is not very large. However, the difference with respect to a normal combination method is significant. The error contribution of errors in the global geopotential model and neglecting the higher frequencies in the outer zone diminished from 10 cm over 100 km to 2 cm over 100 km.

3.3.3 Inner zone error propagation

In the error propagation of the inner zone gravity data it is quite usual to adopt some approximations to simplify the computations and diminish computation time. The approach as described by Strang van Hees was tested versus the straightforward computation of the geoid error. The approximations can affect the geoid error with a factor 2 (optimistic or pessimistic) since the high frequency error by the inner zone gravity data is a very local effect and depends very much on the local data distribution and data density. The propagated error from the gravity anomalies in the new Dutch gravity dataset in the inner zone is of sub-cm level for distances upto 100 km. The newly measured gravity dataset in the Netherlands in very good and has no significant systematic effects.

3.3.4 Inner zone geoid computation techniques

Another important aspect of the geoid computation is the choice of using numerical integration of Stokes' integral or using least squares collocation for the inner zone gravity data contribution. In a first step it was shown that these two methods do not yield identical results in general practice (De Min, 1993), later it was explained how the least squares collocation method has to be modified to yield identical results as numerical integration (De Min, 1994b). An optimal combination method of numerical integration and collocation was also given.

At the same time an old numerical integration technique, was studied again. This method is based on a triangulation network between the original gravity points. This triangulation network is used to give area-weights to the gravity points and there is no need for computing mean blocks in advance. From tests with several datasets it was found that no significant differences with numerical integration over mean blocks are found when a sufficiently dense gravity dataset is available (Burger, 1993; De Min, 1993). The method can have some advantages when the data density is not very homogeneous.

For the Dutch geoid computation procedure it was decided to use numerical integration over mean blocks of about 5x5 km^2 upto 5 degrees from the geoid computation points. One reason is that this method is consistent with the formal error computation, in contrast to least squares collocation, another one that the density of the available gravity data is very high with respect to the gravity signal variation in space, so that no significant discretization error is introduced ($<$ 5 mm).

In this numerical integration over mean gravity block values it is important to integrate the Stokes' function over the block areas. This could also be concluded from the already mentioned comparison with least squares collocation. The optimal way to compute these integrated Stokes' function values is described by (De Min, 1994c).

3.3.5 Fast evaluation techniques

The evaluation of numerical integrals like Stokes' can be done very efficiently by applying Fast Fourier Techniques. Until Strang van Hees (1990) presented a completely new idea, FFT was always applied in flat surface approximation which needs many approximations. Strang van Hees suggested a new approach where the integral is evaluated on the sphere, and not on a plane, with only few approximations. Later, Haagmans et al. (1993) further developed this method so that no approximations are necessary at all, and exactly the same result is obtained as would be from straightforward numerical integration. This 1D-FFT method is now internationally widely in use in geoid computation procedures and will also be used in the Dutch geoid computation procedure.

3.3.6 Final geoid quality

If the gravimetric geoid computation is performed in the above described way a gravimetric geoid is obtained with a precision of about 2-3 cm over 100 km distance. Haagmans & Van Gelderen (1991) have shown that deviations upto 40% are possible for the formal geoid error from global geopotential coefficients when error degree variances are used instead of the correct and complete variances and covariances. This means that the formal Dutch geoid error can also be somewhat larger (or smaller). The mentioned error is of long-wavelength character and it is therefore possible to correct the gravimetric geoid using external geoid heights. Also for this reason a new measurement project has been performed of the NEREF-network (the first order GPS network in the Netherlands) in 1994 and it is expected that the ellipsoidal height differences upto 200 km can be determined with a precision of 1 cm. Using these 20 NEREF points covering the entire Dutch area, it is possible to correct the gravimetric geoid and obtain a GPS/gravimetric geoid with a precision of 1 cm over all distances. This geoid result can be used to determine orthometric heights by GPS measurements.

In 1996 a GPS network will be finished by the Rijksdriehoeksmeting. This network consist of about 500 stations with inter-station distances of 15 km. The expected precision of the height component is 1 cm for distances upto 50 km, so that a very good control of the GPS/gravimetric geoid will be possible. There are also about 35 deflections of the vertical available which will also give an independent estimate of the gravimetric geoid quality.

3.4 Other work in this area

3.4.1 Orthometric corrections

Strang van Hees (1992) developed a new method to compute orthometric corrections. By rewriting the conventional formula, he arrived at an expression which is mainly dependent on the gravity values and heights of the begin and end points of a levelling line. This in contrast to the original formula which is not very convenient in practice, since all gravity and height values along the levelling line are accurately needed, and the final orthometric correction consists of three large values which add up to one small value.

3.4.2 Radon transform for improved interpolation

Radon transform methods have been found which can be used to indicate possible line structures in undersampled signals. Typical examples of such undersampled signals are altimetry tracks in across track direction and all other kind of profile based measurements. Software has been developed where line structures are detected in such datasets and based on these detected line structures a priori information can be added. In this way the computer replaces the person behind the screen who has to detect such possible line structures visually. First tests (Hanssen, 1993; Haagmans & Zhou, 1994) show very promising results. Further modifications of the method are necessary for improvement of the automated interpolation of profile based datasets.

3.5 Conclusions

Many efforts have been put in the determination of the best possible geoid for the Netherlands during the last four years. A completely new gravity network, both on land and sea, has been measured. Within the framework of the establishment of the geoid computation method to be used, many parts of this procedure have been studied in detail and some improvements have been made and understanding of some methods have been increased. The definition of the geoid computation procedure together with the new gravity data and the external geoid height information from GPS and levelling and deflections of the vertical, supplies the Netherlands with a 1 cm precision relative geoid, which can be used for levelling by GPS.

3.6 Publications

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4. Theory and evaluation

4.1 Estimation and quality control

4.1.1 Real-time quality control of dynamic positioning systems

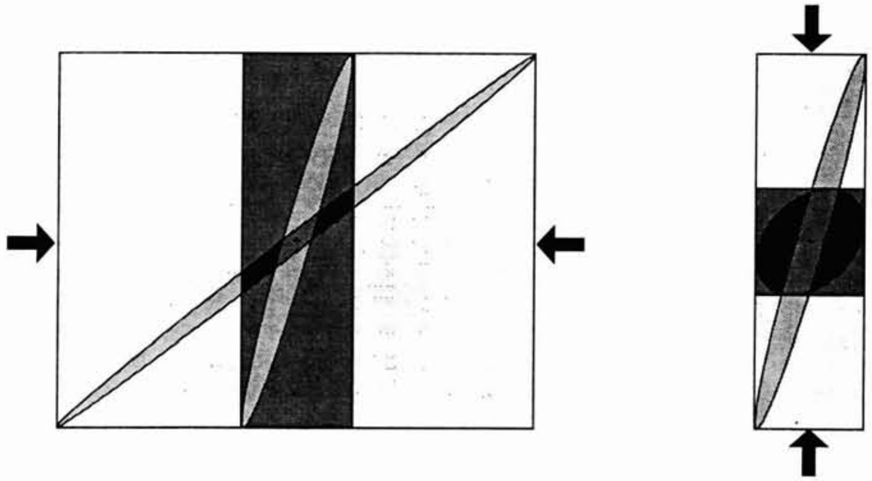
Real-time estimation of parameters in dynamic systems becomes increasingly important in the field of high precision navigation. The real-time estimation inevitably requires real-time validation of the models underlying the navigation system. A real-time recursive testing procedure that can be used in conjunction with the well-known Kalman-filter has been developed in recent years. This research has resulted in the development of a Detection, Identification and Adaptation (DIA) method for the real-time quality control of integrated navigation systems [1-7]. The DIA-method consists of three steps: 1) Detection, 2) Identification and 3) Adaptation. The objective of detection is to test the overall validity of the mathematical model. After the overall model has been invalidated a search among all candidate model errors is performed to identify the most likely model error and most likely starting time. Adaptation follows identification and is needed to eliminate in real-time the presence of identified biases in the filtered statevector. The DIA-method is complemented with diagnostics for the design of integrated navigation systems.

The method has recently been successfully implemented for GPS integrity monitoring purposes. Development and implementation for rapid-static GPS surveying is planned. The Survey Department of Rijkswaterstaat together with the Hydrographic Service of the Royal Netherlands Navy are currently working on implementing the method for their dynamic positioning applications.

4.1.2 The Least-Squares Ambiguity Decorrelation Adjustment

An important estimation and validation problem where the parameters fail to range through the whole of $\mathbb{R}$ occurs in the field of GPS carrier-phase processing. In order to enhance the precision of the positioning results, the integerness of the GPS ambiguities is included into the model as a priori information. Least-squares estimation of the integer ambiguities is however a far from trivial problem if one aims at numerical efficiency. Near real-time algorithms are however needed for applications as rapid-static surveying and dynamic positioning. The topic of fast estimation of the integer ambiguities has therefore been a very rich source of theoretical GPS research over the last decade. Nevertheless, current methods are still not satisfactorily, both from a theoretical as well as operational point of view. Recently however, a new method has been developed that enables an extremely fast integer least-squares estimation of the ambiguities. This is the Least-squares AMBiguity Decorrelation Adjustment (LAMBDA) method [8-15].

The method has been devised to efficiently solve for the integer least-squares ambiguities of the carrier phase observation equations. The method consists of two steps. A first step that constructs an ambiguity transformation allowing one to reformulate the original estimation problem as a new, but equivalent problem that is much easier to solve. The transformation aims at a decorrelation of the least-squares ambiguities and it makes use of integer approximations of the fully decorrelation conditional least-squares transformation. As a result the transformed ambiguity search space is far less elongated than the ambiguity search space based on the original double-differenced ambiguities (see figure).



In the second step, sharp bounds are formulated for the individual ambiguities. This is accomplished by again making use of the concept of conditional least-squares. In this case a sequential conditional least-squares adjustment on the ambiguities is carried, thus allowing one to reformulate the quadratic objective function as a sum-of-squares in the differences of the least-squares ambiguities and their sought for integer counterparts. Since the first step results in largely decorrelated ambiguities with a very high precision, the search based on the sequential bounds can be executed very efficiently.

The performance of the LAMBDA-method, in terms of the amount of decorrelation that can be achieved, is dictated to a large extent by the signature of the spectrum of conditional variances. In particular the large discontinuity which is typically present in most GPS-spectra allows one to achieve a significant flattening and lowering of the spectrum after the transformation. Various GPS-spectra for different measurement scenarios have been analyzed and it has been shown to what extent these spectra can be flattened and lowered. As a result very promising results have been achieved, which are relevant for both rapid-static surveying as well as navigation applications. Up to this point however, the spectra have been based on models which are typically used for short baseline applications. Current research is directed to analyze the GPS-spectra when based on models that explicitly account for additional geometrical and/or physical effects (e.g. ionophere, troposphere, instrumental biases). In case the ionosphere is explicitly accounted for, this leads to a rank-defect integer least-squares problem. Theoretically, this problem has now been solved in the sense that an admissible ambiguity transformation has been found that eliminates the rank defect.

4.1.3 SCAN-3

The adjustment software, developed by the LGR since 1977 for the adjustment of levelling and horizontal surveying networks, has been completely re-designed.

The new SCAN-3 software is optimized for the adjustment and quality analysis of geodetic networks in one-, two- and three dimensions, also it is relatively easy to add new types of observations. Presently SCAN-3 is able to adjust simultaneously height differences, directions, distances, GPS vectors, photo-coordinates, FRANK data and coordinates in many different forms and systems. SCAN-3 is a stand-alone adjustment and quality analysis software package, but the kernel of SCAN-3 is also used by other software products of the LGR. E.g. for the processing of detail measurements, developed in cooperation with the Cadastre, and for the analysis of land subsidence from levelling data, on behalf of the Nederlandse Aardolie Maatschappij (NAM) and the Survey Department of Rijkswaterstaat.

4.2 Positioning

4.2.1 GPS modelling for fast static relative positioning

The Global Positioning System (GPS) is used for a wide variety of applications, ranging from tectonic plate studies, via surveying to navigation. The models for static relative positioning are converging in the sense that the kernel of the model is more or less the same for each static application. The difference then between precise static over long baselines, or rapid static over shorter baselines, is limited to the model extensions. Most of the GPS softwares use double differenced observations. In Delft we have developed a model for undifferenced observations. The advantage of this approach is that it is not as rigid as the double differenced approach. More of the available observations are actually used, especially over longer baselines, and there is more flexibility in the choice of parameters and stochastic models. Also, it was easier to implement the quality analysis for undifferenced observations. Special emphasis in the research has been given on the estimability of parameters and the rank defects, and the integer least-squares estimation and validation of the phase ambiguities.

4.2.2. A recursive procedure for GPS differential corrections

The DGPS technique can considerably improve the accuracy of stand-alone GPS positioning, since biases inherent in the latter technique are greatly reduced or even eliminated. But the improvement depends on the distance between the user and the reference station (spatial correlation), the latency of differential corrections (temporal correlation), and the quality of differential corrections. Therefore, how to correctly generate differential corrections is one of the keys to the DGPS positioning technique. For the implementation of a good quality control procedure, it is essential that the stochastic behaviour of the observations and process dynamics are modelled correctly.

A new algorithm has been developed and tested for generating differential corrections along with a recursive quality control procedure, which has some distinct features [16, 17]. First, it directly uses code and carrier observations in the measurement model of a Kalman filter, so that the measurements do not become correlated in time, as happens with carrier filtered code observation or sequential differences of carrier observations. Second, all of its state estimates including differential corrections are not affected by the opposite influence of the ionosphere on code and carrier observations. Third, it can perform recursive model testing along with the generation of differential corrections, so that the quality of all state estimates can be guaranteed with certain probability. Fourth, in addition to generating differential corrections, when carrier observations available, the algorithm can also produce information on the variation of ionospheric delays and on that of code biases. Fifth, the algorithm can be applied in the case that code biases are significantly present or absent. In the former case, the effects of code biases on the estimates of differential corrections can clearly be shown. Whereas in the latter case, the algorithm can generate unbiased estimates of differential corrections.

4.2.3 On the connection of geodetic pointfields

The connection of geodetic pointfields is an important and ever-recurring problem in surveying. The problem can be recognized in the management of coordinate data bases, when partially or completely overlapping coordinate sets need to be merged. It can be recognized in the densification of geodetic networks and it is related to the problem of coordinate transformations between different reference frames. Depending on the application, different methods of connection can be distinguished (rigorous least-squares, pseudo least-squares, overdetermined transformation) and within each class of connection method, also different numerical procedures can be distinguished. A first start in formulating a general framework for the connection of geodetic pointfields has been made. It shows the interrelations between the different methods and numerical procedures, it identifies the set of assumptions on which the different methods are based, and it describes the properties of the different methods in a qualitative sense.

4.3 Deformation analysis

4.3.1 1D Deformation analysis from levelling networks

In 1990 the research project "Geodetic Deformation Analysis" between the LGR, the NAM and the Survey Department of Rijkswaterstaat was started. The objective of the project is the development of a modular software system for the multi-epoch analysis of one-dimensional deformations [18-20].

In accordance with the usual phases of the geodetic deformation analysis this project was defined to contain the following steps:

1. Single epoche evaluation of the levelling data available.
2. Stability evaluation of reference benchmarks.
3. Estimation of the most likely deformation model.

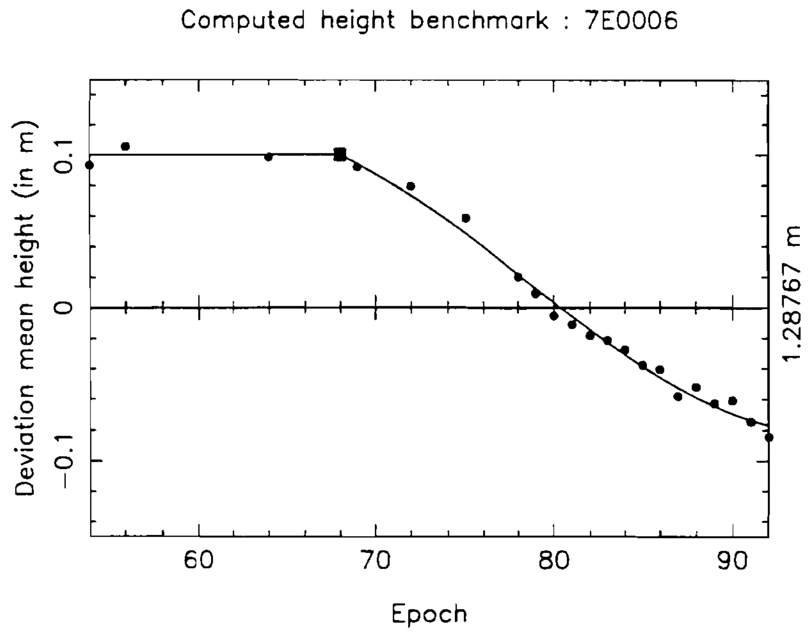
In 1993 the project was focused on the third item. The aim of the third phase was to arrive at the most likely mathematical model describing the deformation pattern underlying the data. In this case the data was coming from the multi-epoche levelling campaigns for monitoring land subsidence due to gas extraction in Groningen. Conformably to the former steps in the project a consistent mathematical model is obtained by means of an integrated application of hypothesis testing for estimation of the functional model and variance component estimation to modify the stochastic model.

The estimation of the deformation model consists again of three different steps, i.e.

Estimation of a 1D polynomial model per benchmark
The time-dependent behaviour of an object point is described by a polynomial. The most suitable degree of the polynomial is determined as well as the possibility of a so-called breakpoint (that point in time from which, due to the gas extraction, the benchmark enters the subsidence area).

Estimation of a 3D polynomial model per selection of benchmarks
For a number of points (covering an area) a 3D polynomial is estimated as a function of time and position (x,y). This model can be used to identify points with a deviant behaviour from the surrounding points and for an optimal estimation of heights at grid points.

Comparison with external height-information
In the Groningen case predictions from geophysical models are available and have to be compared with the levelling results. Differences are analyzed by estimation of corrections of systematical deviations and the determination of a covariance function for the remaining stochastic deviations.



Subsidence of height benchmark 7E0006: a Cubic polynomial is estimated after a breakpoint in epoche 1968.

4.3.2 Optimization of the Groningen deformation measurements

On behalf of the Nederlandse Aardolie Maatschappij B.V. (NAM) some studies have been done on the optimization of the measurement design and the frequency of the Groningen levelling networks for monitoring the land subsidence due to gas extraction.

A first study was concerned with the influence of the size and the density of the networks on the possibility of detection of subsidence. Two alternatives have been considered, i.e. the present large and small levelling networks. For both configurations design computations have been carried out involving two epoches, using realistic model assumptions based on the experiences of previous research.

A second study aimed at obtaining a first impression on the possibility of GPS measurements for monitoring land subsidence. Design computations have been done for the combination of levelling and GPS measurements and the influence of additional GPS measurements on the possible detection of subsidence. It was shown that at least a precision of half a centimeter for 15 kilometer GPS-baselines is necessary for significant improvements.

4.3.3 SCAN-DEFO

As a part of the project on deformation analysis a software system to perform the computations during the project was developed. In 1993 a provisional release of the system has been finished. The software can be divided in four parts, conform the stages in a typical project as mentioned earlier. The software was written in standard Fortran 77 and runs on VAX/VMS-systems as well as on HPUX-systems. The software is menu-driven, whereas some parts of the software can be run in background batch-processes.

Epoche analysis
This part of the software provides the necessary tools for analyzing the observations in a single epoche. Apart from the traditional Delft method for adjustment and testing several other tools are available, including graphical and numerical presentations, interactive data-editing, computation of the loop misclosures etc.

Analysis of the stability of the reference points
This part of the system takes care of testing the stability of the reference points. The heights of the reference points as computed in the previous step are used as observations here, together with their stochastic model. This results in one set of observations for each epoche. Assumed is stability for all reference points (null hypothesis). This model is computed (LSQ-adjustment and testing) and depending on the results of this computation the model can be adapted. This procedure is repeated until a satisfying result is obtained. The process can be executed manually or (mostly) automatically. Apart from the computations several tools for interactive data-editing are provided.

Deformation analysis
Currently the software is capable of computing two types of models. One being polynomials in time for separate points, the other being 3D polynomials in time and position for a group of points (area). Both routines are based on the theory described earlier, a starting model is specified, computed and tested. Apart from the traditional tests (global test and conventional alternative hypotheses), also some non-conventional tests are performed. According to the results of these tests the model can be adapted. This process is repeated until a satisfying result is achieved. Both routines can be used interactively, which gives the possibility for the user to interact with the process, or in background, with no interaction. Results can be presented both numerically and graphically.

Analysis of (external) predictions
This part of the software provides the user with a kind of toolbox, giving him the possibility of comparing some external prediction of the subsidence with the results found during the actual analysis. All tools provide for getting some grip on the quality of the prediction. The tools include some specific mathematical tests on the prediction, as well as ways of selecting specific parts of the data.

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5. Physical interpretation

5.1 Land subsidence research in the Netherlands

5.1.1. Introduction

Geodetic measurements and reference frames have always played a significant role in many fields of earth science and civil engineering. Relatively new perspectives are offered by the availability of long time series of geodetic measurements, especially levelling data. These long time series can offer valuable constraints on models developed in other fields of earth science including oceanography.

A subject of particular interest for the Netherlands is the protection of our country against sea-level rise. With about 60% of the Netherlands below Mean High Water, sea-level rise is a subject of major concern. The expected acceleration of sea-level rise due to the greenhouse effect puts even more emphasis on this subject.

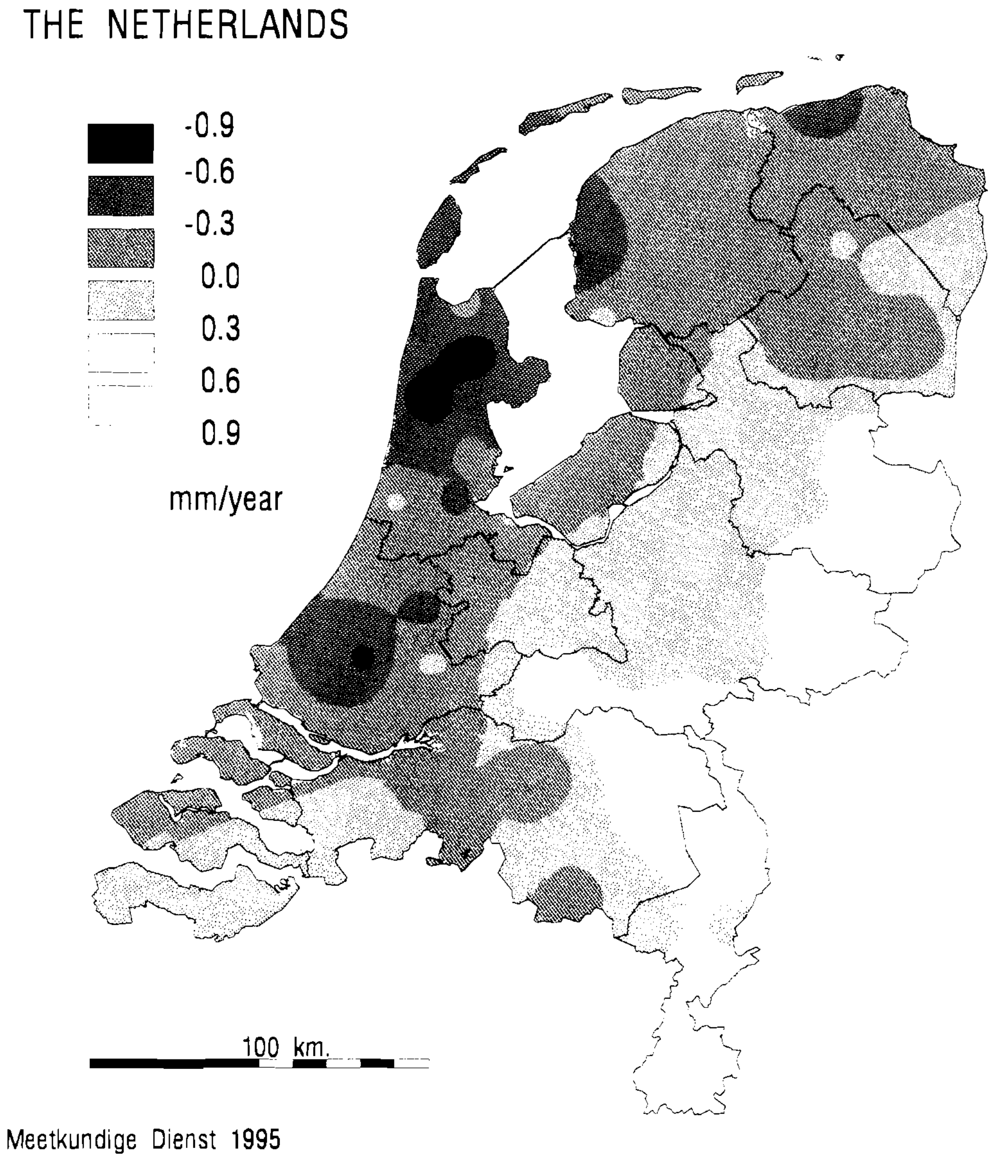
For the future protection of our country, relative sea-level rise is, to a certain extent, the most important parameter. However, to be able to predict future sea-level rise as accurately as possible, a quantitative understanding of all mechanisms contributing to relative sea-levelrise is of great importance. It can help to reduce the uncertainties we have to deal with in defending our country against the sea. The long time series of levelling data that are available in the Netherlands, offer the opportunity to separate between the eustatic part of sea-level rise, and the contribution of land subsidence.

5.1.2. Regional land subsidence

At the end of the 80's, a project was started to re-analyse precise levelling data that had been collected in the period 1926-1987. These measurements were performed to check the stability of the network of underground benchmarks, which serves as the backbone of the Amsterdam Height Datum (NAP). Most of these benchmarks are placed in the upper reaches of the Pleistocene sands during the 2nd Primary Levelling (1926-1940). By then, it was presumed that these layers would be perfectly stable with time. However, when new data came available after World War II, discrepancies were observed between the new levelling data and the heights of the underground benchmarks, which resulted from the 2nd Primary Levelling. More recent campaigns have shown that these discrepancies increase with time.

The analysis was performed by kinematic adjustment of data of three first order levelling campaigns (the 2nd (1926-1940), 3rd (1950-1959) and 4th (1965-1978) Primary Levellings), and some selected second order levellings from the period 1980-1987. In the kinematic adjustment, height, velocity and acceleration of the benchmarks is computed. The results show that significant vertical movements appear in the upper reaches of the Pleistocene sediments. All movements appear to be linear with time.

The movements of the 53 underground benchmarks give information on the regional land subsidence that takes place in the Netherlands. Several patterns of motion are clear from this picture (see figure). First, a general tilting of the Pleistocene layers (subsidence



Vertical movements of underground benchmarks 1926-1995 (mm/year). Results of kinematic adjustment of 1st and selected 2nd order levelling data.

in the North and West, relative uplift in the Southeast) can be observed. The cause of this tilting towards the North Sea can probably be found in the post-glacial rebound and hydro-isostasy, both related to the glacial unloading of northern Great Britain and Fennoscandia (18000-12000 B.P), and the concomitant meltwater loading of the adjacent seas and ocean. Superimposed on the tilting, a striking correlation is observed between the pattern of vertical motion and well known geological structures in the Dutch subsoil.

This correlation is a strong indicator for neo-tectonics (and corresponding compaction) to be the mechanisms behind these large-scale movements.

Whereas the correspondence between the patterns of land movement and geological features is not a big surprise, the absolute rates of movement are. Velocities vary from −8cm/cy in the Northwest to +7 cm/cy in the Southeast, and these velocities are quite high compared to average velocities on geological timescales, as derived from sediment thicknesses and other sources. The present day high velocities however, correspond to observations from other sources, which also indicate that short-term vertical motions may significant differ from long-term averages.

5.1.3. Analysis of local vertical movements

Having analysed rates of vertical movement for 53 underground benchmarks, the research was continued with the analysis of movement rates for all benchmarks in the Netherlands. The total number of benchmarks, which can be found in houses, churches and all kinds of civil constructions, and which are available for all users of height information, amounts to more than 50,000.

For these benchmarks, about 250,000 height values have been collected in the period 1875-1994, which have been measured by means of hydrostatic as well as 1st, 2nd and 3rd order spirit levelling. To allow a smooth handling of all these data, a GIS application was developed.

In this application, rates of vertical movement can be calculated for all benchmarks by means of linear trend analysis. The tool enables the application of numerous selection criteria, the analysis of changes in time, the choice between several interpolation techniques etc. The GIS application proves to be an excellent tool for the analysis of land subsidence in the Netherlands.

The results of a movement analysis for all benchmarks shows that, disregarding the high frequency signals, the subsidence pattern of surface benchmarks corresponds quite well with the regional picture. The rates of movement however are much higher. Subsidence rates up to 50 cm/cy along the North Sea coast are not uncommon. Two mechanisms are thought to be the main contributors to this subsidence: the movements of the constructions in which the benchmarks are foundated, and the compaction of the Holocene sediments (with thicknesses up to 25 m) covering the Pleistocene sands.

Detailed information on vertical movements was used in a case study in the Southeastern part of the Netherlands. In the early morning of April 13, 1992 an earthquake took place at one of the faults forming the Peelboundary system, which is the most prominent fault structure in the Dutch subsoil. This earthquake had a magnitude of 5.9 on Richter's scale and was the strongest ever recorded by instruments in the Netherlands. Statistical research indicates that earthquakes of this magnitude occur in this area only once per 200 years.

Only several weeks after the events, precise levelling measurements were carried out across the Peelboundary fault. The same run had been monitored frequently since several decades for the purpose of measuring height changes across the fault. The new measurements showed that no significant displacement had taken place as a result of the earthquake. This was not surprising: with the focal centre of the earthquake at 23 km depth and a vertical displacement of about 15 cm, no traces were expected at the surface.

Geodetic observations were also used in an interdisciplinary research for the tectonic structure of the fault system. Detailed geomorphological, geological and subsidence information was used in this study (Van den Berg et al., 1994). The geodetic measurements proved to be a valuable source of information for putting constraints to the structural hypotheses.

5.1.4. Present day research on land subsidence

In cooperation with the Geological Survey of the Netherlands and several universities, research is going on to investigate the contribution of the various mechanisms to land subsidence. Corresponding to the different scales on which the mechanisms are manifest, the research is split in two projects.

In the first project, post-glacial rebound, hydro-isostasy and tectonics are investigated. In the second project, attention is paid to shallow compaction and "foundation subsidence". Input from engineering geology and geomechanics is required to solve the letter.

In both projects, 3-D and 4-D Geographical Information Systems play an important role for data-management and analysis purposes.

5.1.5. Future monitoring of land subsidence

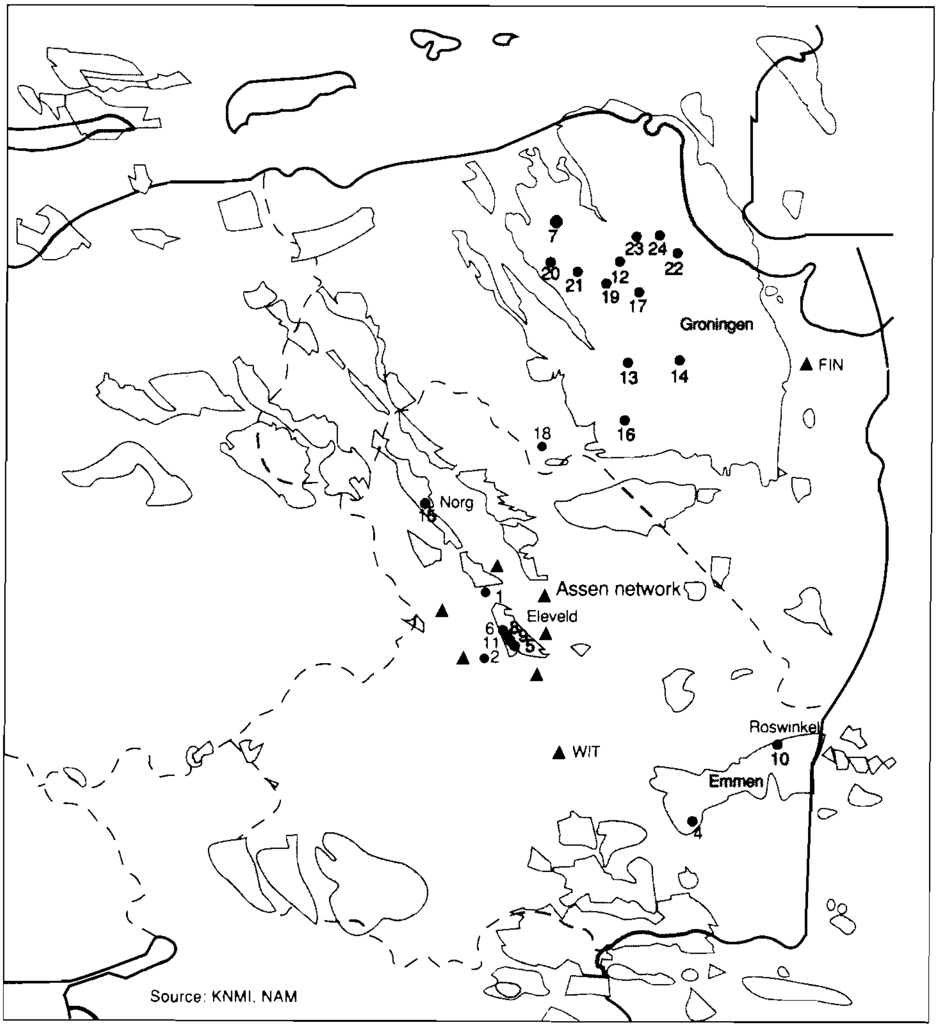
With the advance of geodetic space techniques, new perspectives are being offered for the monitoring of land subsidence and sea-level rise. Since 1990, 3 GPS-campaigns have been carried out at tide gauges, connecting these gauges to the geodetic reference points of the EUREF GPS-network. More on these campaigns can be found in Chapter 1 on Control Surveys. The same holds for plans to execute in the years 96-97 a Fifth Primary Levelling, consisting of both spirit and hydrostatic levelling ans GPS and absolute and relative gravity observations.

Space geodetic techniques offer new challenges and perspectives for researchers on sea-level rise and related subjects. This implies a need for better cooperation and coordination between international research groups and monitoring agencies. The Survey Department of Rijkswaterstaat, in cooperation with colleagues of Delft University of Technology, therefore has put forward a proposal to establish such an improved cooperation between countries in the North Sea and surrounding area. This proposal to the EU, called NOSS (North Sea Sea-level Observing System) in principle covers all research and monitoring activities concerning the monitoring of sea-level rise.

5.2 Earthquakes and gas production

From the end of 1986 to August 1993 24 earthquakes were recorded in the northern part of the Netherlands. The next figure shows a summary of the epicentres. Twelve of the 24 tremors were recorded only by the borehole seismometers at Finsterwolde. These seismometers have been in operation since July 1992. All of the epicentres were located either within gas fields or in their immediate surroundings. The earthquakes of magnitudes 1.4 to 2.8 on the Richter scale occurred at shallow depth (ca. 3 km or less). By contrast, the tectonic earthquakes in the southern part of the Netherlands occur at much greater depths (5 to 30 km).

An earthquake arises when the shear stresses within the bedrock exceed a given threshold value. This value is determined by the strength of the rock and that of the stress field. In this context, existing faults often form zones of weakness. The question regarding the relationship between gas production and earthquakes was investigated. This was done by calculating the stress changes resulting from pressure drops in gas reservoirs, in a mathematical model. For this purpose, the strength of the rock was used as input data, along with other geomechanical characteristics. These calculations are quite complex, since any shift along fault lines also has to be taken into consideration. The results clearly indicate that, broadly speaking, there are a few different mechanisms for existing faults to be re-activated by gas extraction.



Epicentres of recorded earthquakes in the northern part of the Netherlands (dots). The triangles indicate the positions of seismic stations. Gas fields are indicated in grey.

During gas production, gas pressure in the reservoir gradually declines. This reduction in counter-pressure results in increased pressure on the reservoir rock, the total pressure exerted by the weight of overlying rock remaining the same. As a result of this increased pressure on the rock matrix, the reservoir is compressed, an effect described as compaction. Such compaction at depth results in ground subsidence at the surface. Whereas, in the central areas of large gas fields, ground subsidence is almost exactly equal to the compaction at reservoir depth, in small fields such subsidence is only a small fraction of the total compaction.

Earthquakes can arise along faults where the level of compaction on one of the fault differs from that on the other. This is referred to as differential compaction. It can occur where the edge of a gas field is sealed by a fault and also at faults within the field itself. In most cases, differential compaction is a very gradual process. In places where movement along faults in the bedrock is obstructed, due to the presence of conglomerate for example, large shear stresses can build up. When these shear stresses exceed a given threshold value, this barrier will be shattered, producing a sudden shift giving rise to an earthquake.

Another mechanism is applicable to faults situated further away from the gas field. The majority of the gas fields in the north-eastern part of the Netherlands is located underneath a thick salt layer. The properties of this rock salt, especially its fluid-like behaviour, are of critical importance for redistribution of the stresses and for movements far beyond the immediate vicinity of the reservoir under production. Even in these remote locations such redistribution of stresses can, dependent upon the predominant tectonic stress, produce sudden sliding motions along existing fault planes. The amount of energy released by such settling, which is principally determined by natural tectonic processes gives rise to a "triggered earthquake".

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