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Chapter 2

Geodetic Deformation Analysis in The Netherlands: Past, Present and Future



**Gini Ketelaar, Hermann Bähr, Raoul Quadvlieg, Hans van der Marel,
Freek van Leijen, and Ramon Hanssen**

Abstract This article reflects on the geodetic measurement techniques and processing methodologies that have been applied for subsidence monitoring in the Netherlands since the 1960s, driven by the legal obligation (according to the Dutch Mining law) for Nederlandse Aardolie Maatschappij (NAM) to monitor subsidence due to hydrocarbon extraction. Traditional geodetic techniques such as leveling have been supplemented with satellite based techniques such as GNSS (Global Navigation Satellite System, GPS) and InSAR (Interferometric Synthetic Aperture Radar, satellite radar interferometry). Processing methodologies, all with a solid foundation in the Delft adjustment and testing theory, have developed over the decades by and in collaboration with Delft University of Technology. All these developments undoubtedly carry the fingerprints of the scientific contributions of Prof. Teunissen. Precise and reliable estimation of deformation signals is more relevant than ever, with shallow subsidence issues induced by climate change and the millimetric computations required to determine relative sea level rise.

2.1 Introduction

The significance of the discovery of the giant Groningen gas field can hardly be exaggerated. When Ben van Beurden ‘Shell’s CEO at the time—visited NAM in 2022, he reminisced that when he was a boy one of his chores was to fill the coal scuttle. Compared to later jobs in his life this must have been only a so-so task—especially in the cold weather when he had to traipse out to a shed in the back garden. He didn’t like the coal furnace because he had to wash himself next to it with a washcloth that did not stay hot long enough. Luckily, during the 1960s Groningen’s gas fueled an energy transition. The Netherlands and large parts of

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Europe, moved away from coal to cleaner gas. Houses became more comfortable thanks to the arrival of central heating, warming up every room and allowing hot showers, which also made a hygienic impact. NAM generated several hundred billion euros of wealth for the Dutch society and a significant part of the earnings of the two parent companies Shell and Exxon were re-invested in the Netherlands. This investment led to the opening of the Pernis refinery, the largest in Europe, as well as enabling the growth of many more energy intensive heavy industries in the region. The rise of gas as an energy source in the Netherlands also allowed for the development of gas heated greenhouses to grow vegetables and the use of ammonia-based fertilizers using natural gas as feedstock for instance to grow the world famous Dutch tulips. This windfall was also a major enabler of social mobility. Ben van Beurden even credited it in part in allowing him to pursue university studies that, being from a humble background, might have otherwise not been possible.

After 50 years of production it became apparent there were also major downsides to the Groningen gas production and clearly the tremors it caused has impacted the well being of the people of Groningen. But well before the earth tremors caused by the production of the Groningen gas led to the shut in of the Groningen field there was a concern that the compaction of the gas bearing geological formations would lead to subsidence. This was brought to the attention of the public through questions in parliament to the minister in 1962 taking examples of the Bakersfield in the US and lake Maracaibo in Venezuela as analogues. In his reply the minister pointed out the differences in formation depth, composition and consolidation. During that debate it became apparent that there might be up to 400 billion cubic meters of natural gas in the Groningen field, whereas up till then the expectation was that it held some 10 billion cubic meters. Only at the end of the 60's it turned out there was 2900 billion cubic meters in place of which today some 500 billion cubic meters still remain.

Expertise on compaction and resulting subsidence was available and J. Geertsma of the Koninklijke Shell Exploratie and Productie Laboratorium (KSEPL) had already studied the compaction of sand stone and published in international journals in 1957 (Geertsma 1957, 1973; Geertsma and van Opstal 1973). In 1963 NAM started an extensive scientific program to research compaction with the most important components:

1. In-situ compaction measurements: in 11 wells gamma-ray marker bullets were placed in the producing formation and by repeat surveys the distance between the bullets was monitored as a measure for the reservoir compaction.
2. Laboratory measurements: cores taken from the reservoir were subjected to pressure tests in the KSEPL to determine the compaction coefficient of the producing formation.
3. Theoretical models: developed to translate the reservoir compaction to subsidence at surface.
4. Shallow compaction measurements: to prevent that all subsidence measured at surface would be related to reservoir compaction also the compaction of shallower layers were monitored. 14 wells were drilled up to a depth of approximately 400 m

and with an extensometer the compaction was measured of the layers of sand and clay.

In 1971 the first subsidence study was finished and the results were reported to the minister of Economic Affairs and the State Supervision of Mines. The main result was that the soil would subside gradually in space and time like a bowl and damage due to local and irregular deformation as happened in Limburg due to coal mines would not occur in Groningen. Based on the available data the expectation at the time was that the maximum subsidence would be around 1 m in the year 2050. It fell on the shoulders of the geodesy discipline to advise survey techniques to measure the subsidence. From 1964 onwards repeated land surveys were conducted to

1. Verify the predicted subsidence and visualize where and when the prediction does not match the subsidence surveys in order to improve the predictions.
2. Map the occurred subsidence as precisely as possible and, based on that, steer water management mitigating measures.

Moreover, the mining law prescribes the Nederlandse Aardolie Maatschappij to regularly survey if and to what extent subsidence is occurring above the gas fields. The 'Meetkundige Dienst' (survey department) of 'Rijkswaterstaat' (the Dutch Directorate-General for Public Works and Water Management), maintains and publishes the height reference in the Netherlands with respect to Normaal Amsterdams Peil (NAP), and issues guidelines for surveys and processed the measurements. These are reported to the State Supervision of Mines, the Provinces, the waterboards and NAM. These NAP registers of Rijkswaterstaat are publicly accessible and every citizen can get an overview of benchmark movements in a particular area. From 1964 it was the Meetkundige Dienst or NAM who carried out the surveys while after 1970 this was done by the major survey contractors in the Netherlands. Through these land surveys it became clear that there was far less subsidence occurring than the first estimate indicated and in 1972 de Meetkundige Dienst issued a press release stating that over the period so far only a third of the predicted subsidence had actually occurred. The press release included a contour map of the subsidence. After these results were confirmed by subsequent land surveys this led to a major revision in 1975 and the estimate of the most subsiding point at the end of the gas production was expected to be in the order of 30 cm (Schoonbeek 1976). This too led to questions in parliament and members expressed a desire to ensure sufficient funds would be made available to compensate for any effects on dykes and the ground water table. It was well known that gas production induced subsidence is primarily affecting water management and can be mitigated by measures taken by the water boards. In 1984, a Subsidence Committee was established based on agreements between the province of Groningen, NAM en the national government. The committee was tasked to decide what measures had to be taken to prevent damage due to gas production induced subsidence and to quantify the costs. The NAM created a fund of approximately 650 million guilders (indexed at 1980) to finance the necessary water management measures. NAM was also obliged to continue the research efforts and update the prediction with an interval of 5 years taking the results of the land surveys

into account. The last prediction dates from 2020 and predicts 44 cm of subsidence for the most subsiding point by 2050 (NAM 2020).

Due to the low signal to noise ratio of the subsidence in Groningen, now typically around 0.05 mm/year over a distance of 100 m, it required continuous innovation to translate the measurements into subsidence due to hydrocarbon production. From the very beginning there was a fruitful collaboration between Delft University of Technology, the Meetkundige Dienst and NAM and the application of the Delft School of Geodesy to the problem of deformation analysis led to scientific breakthroughs and numerous publications. This collaboration continues till today, as subsidence monitoring with state-of-the-art methodologies continues, also after stopping gas production. The discovery of the Groningen field not only led to wealth for the Dutch society but also triggered scientific research that gave Delft University of Technology a world class reputation in the field of deformation monitoring.

2.2 Geodetic Measurement Techniques for Subsidence Monitoring

Since the start of gas production in the 1960s, the following geodetic measurement techniques have been applied for subsidence monitoring:

- leveling,
- gravity,
- GNSS (Global Navigation Satellite System, GPS),
- InSAR (Interferometric Synthetic Aperture Radar, satellite radar interferometry).

The techniques are discussed in chronological order of when they were applied for the first time. At the end of this section, the Integrated Geodetic Reference Stations (IGRS), which are used to collocate the various geodetic measurements, are discussed.

2.2.1 Leveling

As stated, from 1964 onwards, regular leveling campaigns have been performed with intervals varying from yearly to 5-yearly. Networks are connected to a number of underground benchmarks, of which several are outside the area of subsidence. For the most extensive networks, the total length of levelling lines is about 1600 km.

Leveling networks are designed to incorporate redundant observations, that enable the testing and removal of erroneous measurements. Application of the Delft adjustment and testing techniques (Baarda 1968; Brouwer et al. 1982; Teunissen 1985a, b, 2000a, b) have assured the reliability of the height (difference) estimates throughout the years, with the precision of the estimates quantified in the variance-covariance

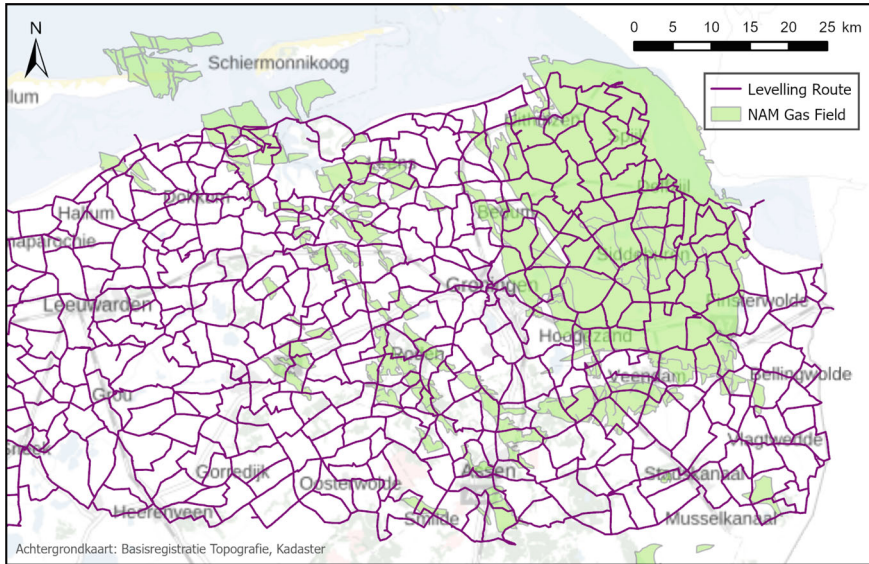


Fig. 2.1 Levelling network of the Northern Netherlands as observed in 2018 in cooperation between Rijkswaterstaat and NAM

matrix. Initially this was done using the SCAN (System for Computerized Adjustment of Network) software developed by TU Delft, first with SCAN-II (Kok 1982; Brouwer et al. 1982) and after 1994 with SCAN-3 (Dierikx et al. 1999). SCAN-3 was eventually replaced by the commercially available MOVE-3 software (Sweco 2008), which is fully compliant with the procedures developed at the Faculty of Geodesy of Delft University of Technology.

Between 1990 and 1994 several studies on the Groningen levelling network were carried out by the TU Delft, resulting in a series of technical reports for NAM (de Heus et al. 1991a, b, 1992a, b, 1993, 1994a) and publications (Verhoef and de Heus 1990; Verhoef and Brouwer 1992; de Heus et al. 1994c, b; Verhoef and de Heus 1995; de Heus et al. 1995; Verhoef 1996; Verhoef and de Heus 1996; Verhoef et al. 1997). An important tool that was used in these studies was the Scan-1Defo software (Joosten and Martens 1991).

In 1991 also a calibration facility for precise levelling rods was established at the TU Delft (de Bruijn 1992; Kremers 1995) (Fig. 2.1).

2.2.2 Gravimetry

Gas extraction, the resulting density changes in the subsurface, and subsidence at ground level, induces gravity changes. Gravimeters can measure absolute subsidence



Fig. 2.2 Gravity stations

with respect to the earth's center of mass. Between 1978 and 1996 several gravimetry campaigns have been carried out, but the applicability for subsidence monitoring stayed in the research domain. In 2015 another (extended) campaign has been performed, initiated by NAM, with the aim to calibrate subsurface scenarios (Eiken 2016; Glegola et al. 2017). This gravity survey, in combination with reprocessed historical gravity data (1978–1996), resulted in measurable and interpretable gravity changes in the Groningen field (in the order of 50–60 μGal), which could be used as constraints in reservoir modeling. However, due to the closure of the Groningen gas field and the slow response of subsurface processes, there are no detectable additional gravity changes expected in the near future. One of the driving factors of the noise level of gravity measurements are groundwater fluctuations (Fig. 2.2).

2.2.3 Global Navigation Satellite System (GNSS, GPS)

In the 1990s, GPS came up as a geodetic measurement technique. Between 1994 and 1997 four GPS campaigns were organized in the Groningen subsidence area (Krijnen and de Heus 1995; de Heus et al. 2000). In a campaign 30–60 points were observed using 5 GPS receivers in 1–2 h sessions. Every point was observed several times, resulting in up to 56 1–2 h sessions per campaign. The average baseline length was about 10 km. The GPS stations were also measured using the leveling technique. Processing of the GPS measurements and the integration with leveling measurements was done by Delft University of Technology (Beckers et al. 1995, 1996, 1997; Martens 1997; Beckers et al. 1998; de Heus 1998; de Heus et al. 2000; Kenselaar and Martens 2000b). The GPS data were processed using an iterative stepwise approach. First the GPS data were processed session by session using the Bernese GPS Software V4.0 (Rothacher et al. 1996). Then the sessions were combined using their full co-variance matrix in a network adjustment with the TU Delft SCAN-3 software (Dierikx et al. 1999). The process involves removal of outliers, estimation of variance components, re-scaling and reprocessing of GPS sessions. The best results are obtained using L1 and L2 phase data with an ionospheric delay

constraint and distinct weighting factors for the horizontal and vertical components, resulting in a precision for the height differences of about 6 mm for an individual campaign (de Heus et al. 2000). In view of the low subsidence rates (several mm/year) in the Groningen area the GPS measurements, at this stage, were deemed not suitable for subsidence monitoring standalone. Their usage stayed limited to test systematic errors in the leveling measurements (de Heus et al. 2000).

In the early 2000s, the precision and reliability of GNSS had developed such that it got accepted by the Dutch mining authority as geodetic technique for monitoring subsidence due to gas extraction with mm/year rates. The major innovations compared to previous campaigns were the use of a network of continuously operating GPS “monitoring” stations on the main land and repeated GPS campaigns in the Wadden Sea area—where levelling is not possible nor permanent GPS monitoring—on clusters of deeply founded benchmarks with much longer observation periods (up to 5 d) per station, in combination with a network of continuously operation “reference” stations outside the subsidence area. The first GPS monitor stations were constructed in 2006. The network of GPS monitor and reference stations of 2018 is shown in Fig. 2.3. After 2018 the network was extended with 30 Integrated Geodetic Reference Stations (IGRS, Sect. 2.2.5), in part to fill gaps in the network and improve the

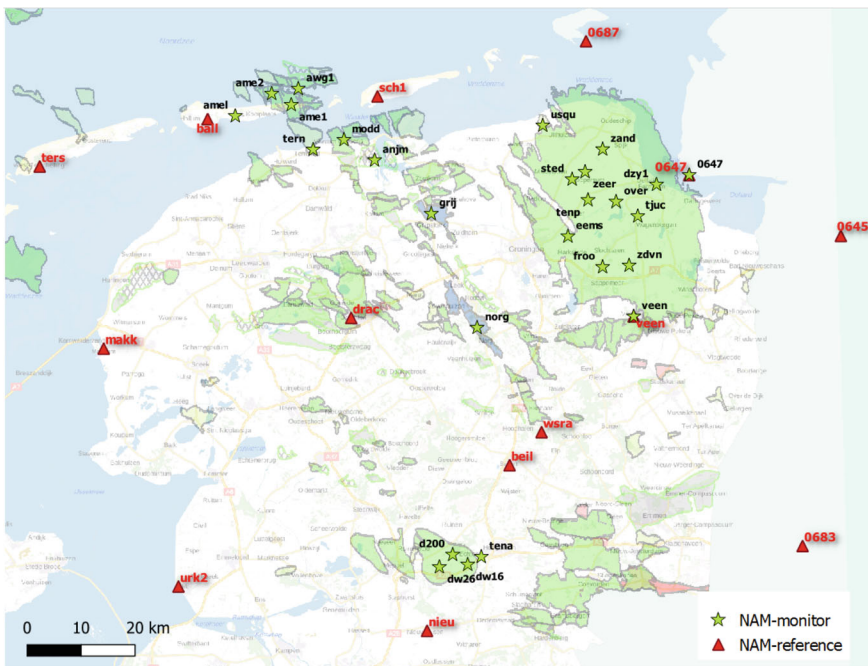


Fig. 2.3 NAM network of continuously operating GPS monitor and reference stations in 2018 (van der Marel 2020). The figure does not show the IGRS stations that were added in 2018 or later

integration with InSAR, and in part to replace several GPS monitor stations at NAM production facilities that were closed.

The first GPS campaign in the Wadden Sea was organized in 2006. The campaigns are repeated more or less every year, and every campaign point is observed every three years. For the campaigns the same equipment is used as for the GPS monitor stations. All antennas are individually calibrated chokering antennas. Four to five campaign points are observed simultaneously. After typically five days of data has been collected, the equipment is relocated to another point. Campaigns can last up to one month, but some campaigns have been split over several shorter periods. Figure 2.4 shows the locations of the GPS campaign measurements. Many of the benchmarks are clustered in 40 clusters of typically three benchmarks each. Only one of these benchmarks is observed with GPS over a five day period. The other benchmarks in the cluster are connected to the GPS benchmark by leveling. A typical benchmark in the Wadden Sea, and setup of the GPS receiver and antenna, is shown in Fig. 2.5. The setup of the GPS antenna is such that the height component measurement is repeatable over time.

The data from both the GPS monitor stations and campaigns is processed together by 06-GPS using the Geo++ GNSMART software (GeoService 2006a, b; Henry and Dentz 2016). Therefore, the results for the GPS monitor stations and campaign data in the area of interest are very homogeneous and also share a common co-variance

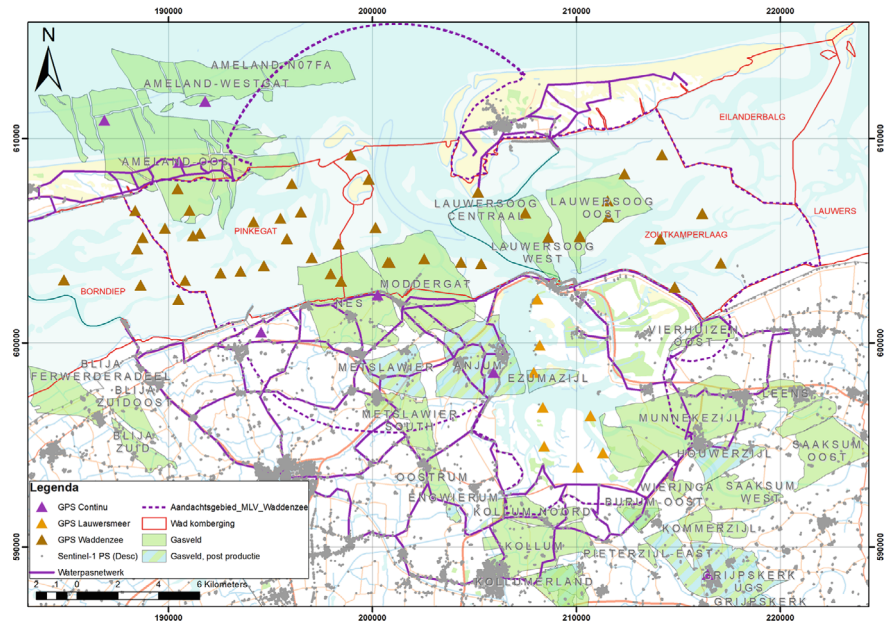


Fig. 2.4 Overview of campaign GPS benchmark clusters in the Wadden Sea area (brown triangles). The figure also depicts continuous GPS stations (purple triangles), leveling networks (purple lines) and InSAR measurement points (grey) (NAM 2021)



Fig. 2.5 GPS measurement setup in the Wadden Sea area. Mutual height differences between the (three) deeply founded benchmarks per cluster location are measured with leveling as well. Campaign GPS measurements are done over 5 d. The height of the GPS antenna is such that it stays above the water line at high tide

matrix (Williams 2015; van Leijen et al. 2017). To obtain a stable reference the coordinates of the NAM reference stations, which are outside the subsiding area, are constrained to reference values. The reference station coordinates are checked every year and if necessary updated (Dentz and Henry 2015; van der Marel 2020).

In the period 2018–2020 an extensive study has been carried out on GNSS processing methodologies for subsidence monitoring by Delft University of Technology (van der Marel 2020). This was one of the studies for NAM and part of the ‘Study and Data Acquisition Plan Induced Seismicity in Groningen’ (NAM 2016). Purpose of the study was to increase transparency, to confirm the reliability of the GPS time series, and to increase insight in the accuracy of the technique. In this study, GPS observations have been processed by three independent parties (06-GPS, the Dutch Kadaster, and Nevada Geodetic Laboratory) using processing methodologies with different characteristics (respectively State Space modeling (SSR), Bernese software regional network processing (BSW) and Precise Point Positioning (PPP)). Delft University of Technology has subsequently decomposed the GPS timeseries (East, North, Up), in order to separate signals originating from other physical causes (such as temperature variations) from the deformation signal. The results of the different processing techniques agreed within accuracy levels, consolidating the reliability of GPS for subsidence monitoring (Fig. 2.6).

Besides the agreement within accuracy bounds between different GNSS processing methodologies, this study also delivered the following insights for high accuracy deformation monitoring:

- The datum needs to be carefully chosen. Usage of ETRF2000 resulted in vertical velocities of -0.9 mm/year for the entire Netherlands, resulting from choices made

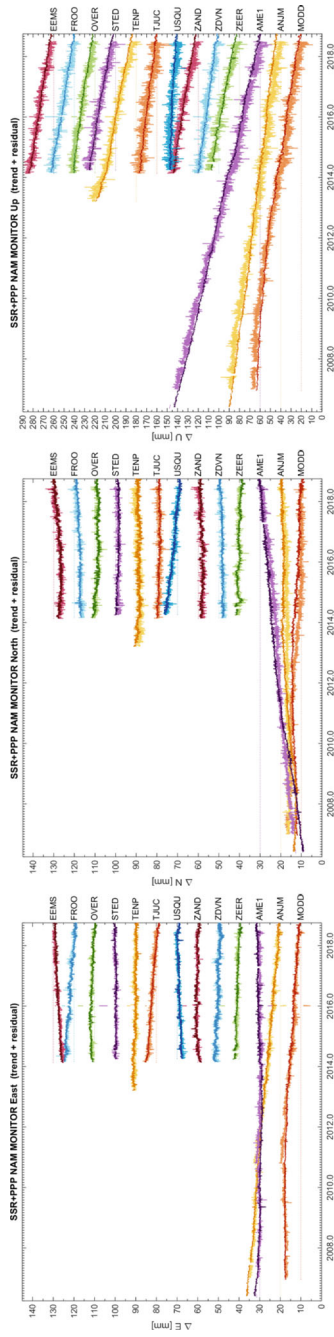


Fig. 2.6 GPS time series East (left), North (middle), Height/Up (right) component (relative, mm), PPP (light) and SSR (dark) solution

in the definition of the datum. Hence, it was recommended to use ITRF as datum of the vertical component.

- Periodograms create insight in the GNSS noise types. For frequencies above 10–20 cycles/year, the BSW and PPP solutions primarily contain white noise only. This allows to make smart choices on the averaging windows in time for data reduction (averaging over 21 d was chosen).

2.2.4 Interferometric Synthetic Aperture Radar (InSAR)

In the early 2000s, first trials were carried out to investigate if subsidence monitoring due to gas extraction could be carried out with the InSAR technique. At the time, the precision and reliability was not sufficient for monitoring subsidence of sub-cm/year rates in rural areas. Hence, a Ph.D. research was initiated in collaboration between NAM and Delft University of Technology, supported by SenterNovem, agency of the Ministry of Economic Affairs (Ketelaar 2008).

The application of InSAR as a geodetic measurement technique for deformation monitoring required a change in mindset towards the concept of measurement points. While for traditional geodetic techniques the measurement points are well defined physical objects in the terrain (such as leveling bolts), the InSAR measurements consist of the superposition of all reflecting targets within a resolution cell of a radar image. Persistent Scatterers (PS) correspond with dominant reflection within a resolution cell, primarily corresponding with (well-founded) objects in the terrain, such as buildings.

InSAR measurements can be either direct or indirect reflections. Measurements originating from indirect reflections may also contain (part) of a shallow subsidence signal. Moreover, the radar satellite monitors the superposition of all deformation signals from space, also settlement of buildings and movements due to shallow or instable foundations. Hence, besides processing geodetic measurements while assuring precision and reliability, the challenge of estimating the deformation signal of interest in the presence of other deformation signals became increasingly important with InSAR as a geodetic monitoring technique (Fig. 2.7).

Due to the lower density of PS in rural areas, the Delft adjustment and testing theory, including the theory developed by Prof. Teunissen for integer ambiguity resolution, has been key to prove that deformation signals (also with low deformation rates over large spatial extent) can be estimated with precision and reliability levels comparable to other geodetic techniques such as leveling.

A system of equations that contains both integer and real-valued (float) unknowns can be solved by Integer Least-Squares estimation (ILS) (Teunissen 2001). The system of observation equations reads:

$$\underline{y} = Aa + Bb + e, \quad (2.1)$$

where \underline{y} is the vector of observations, a are the unknown integer parameters, and b the unknown float parameters. The residual vector \underline{e} consists of model imperfections \underline{s} and measurement noise \underline{n} . In InSAR, the integer valued parameters are the phase ambiguities; the real-valued unknowns the topographic heights and the deformation parameters. The solution of Eq. (2.1) is obtained in 3 steps:

1. integral float solution, obtaining the real-valued estimates \hat{a} and \hat{b} with the corresponding variance-covariance matrix Q ,
2. mapping the float estimates \hat{a} to the integer space: $\check{a} = S(\hat{a})$,
3. computation of the fixed solution of \hat{b} : $\check{b} = \hat{b} - Q_{\hat{b}\hat{a}}Q_{\hat{a}}^{-1}(\hat{a} - \check{a})$.

The probability of correct integer ambiguity estimation is called the *success rate*. Prof. Teunissen has developed a computationally faster methodology as well for resolving integer ambiguities: *integer bootstrapping*. Integer bootstrapping uses a combination of integer rounding and sequential conditional least-squares adjustment techniques. The bootstrapped estimator is not unique and depends on the order of the ambiguities. Both for the ILS and bootstrapping approach, the Least-Squares AMBiguity Decorrelation Adjustment (LAMBDA) method is used (Teunissen, 1993). Hereby, a decorrelating Z-transformation is applied that reduces the sequential conditional variances (Teunissen, 1995), thereby strongly reducing the computation time.

Compared to the leveling technique, InSAR has the advantage that the temporal observation frequency is significantly higher (≥ 1 acquisition per month). In urban areas, the spatial density is significantly higher as well. This increases the insight in the spatio-temporal behavior of deformation signals. Moreover, InSAR is a safe technique: monitoring from space compared to monitoring in the terrain and along roads with land survey techniques (Figs. 2.8 and 2.9).

After explicitly demonstrating the agreement between InSAR and leveling based on geodetic test statistics in various survey registers (reports), InSAR has been accepted as a standalone subsidence monitoring technique by the State Supervision of Mines (SodM) from 2019.

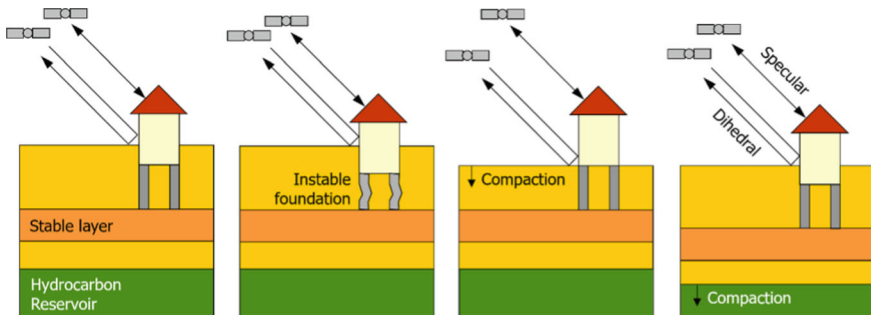


Fig. 2.7 Deformation regimes and InSAR direct and multi-bounce reflections

The test statistic T that can be used to quantify the agreement of displacements estimated from two geodetic measurement techniques can be formulated using the model of condition equations:

$$H_0 : B^T E\{\underline{y}\} = [I \ -I] E\left\{\begin{bmatrix} \hat{\underline{x}}_1 \\ \hat{\underline{x}}_2 \end{bmatrix}\right\} = E\{\hat{\underline{x}}_1 - \hat{\underline{x}}_2\} = 0. \quad (2.2)$$

$$T = (\hat{\underline{x}}_1 - \hat{\underline{x}}_2)^T (Q_{\hat{\underline{x}}_1} + Q_{\hat{\underline{x}}_2})^{-1} (\hat{\underline{x}}_1 - \hat{\underline{x}}_2), \quad (2.3)$$

where $\hat{\underline{x}}_1$ and $\hat{\underline{x}}_2$ are the displacement estimates of each measurement technique, and $Q_{\hat{\underline{x}}_1}$ and $Q_{\hat{\underline{x}}_2}$ the corresponding variance-covariance matrices. This test statistic is invariant for a basis transformation (reference in space and time).

Another way to compare the precision of geodetic displacements is by the ‘Dilution of Precision’ (DOP) measure computed from the variance-covariance matrix (Teunissen and Odijk 1997). This measure is also independent of the spatio-temporal reference (basis).

$$\text{DOP}_{\text{PSI}} = \sqrt{\det Q_\varphi^{-1}}, \quad (2.4)$$

where φ are the PS-InSAR (PSI) double-difference phase observations.

An extended analysis of the precision represented by two variance-covariance matrices is performed through the generalized eigenvalue problem, see e.g., Teunissen et al. (2005). In this way the variance-covariance matrices of two measurement techniques can be compared, e.g. the variance-covariance matrices of the displacement rates estimated from InSAR and leveling:

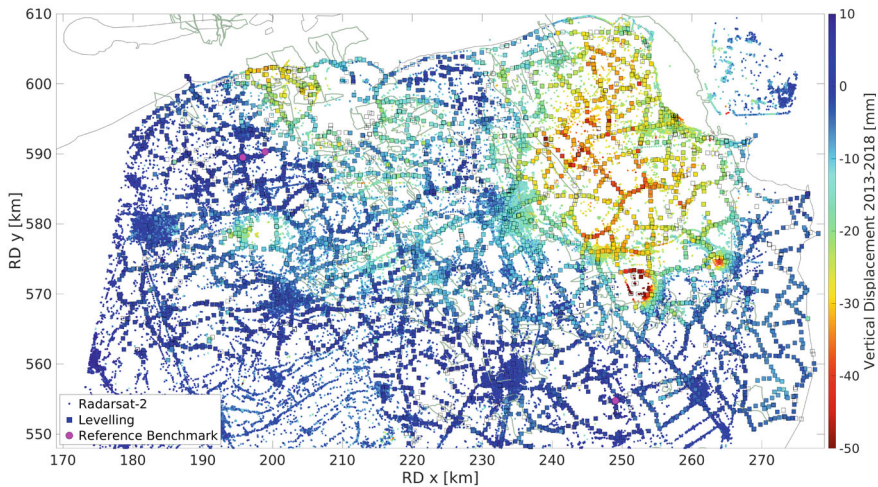


Fig. 2.8 Deformation (mm) by InSAR and leveling in the period 2013–2018 (NAM 2019)

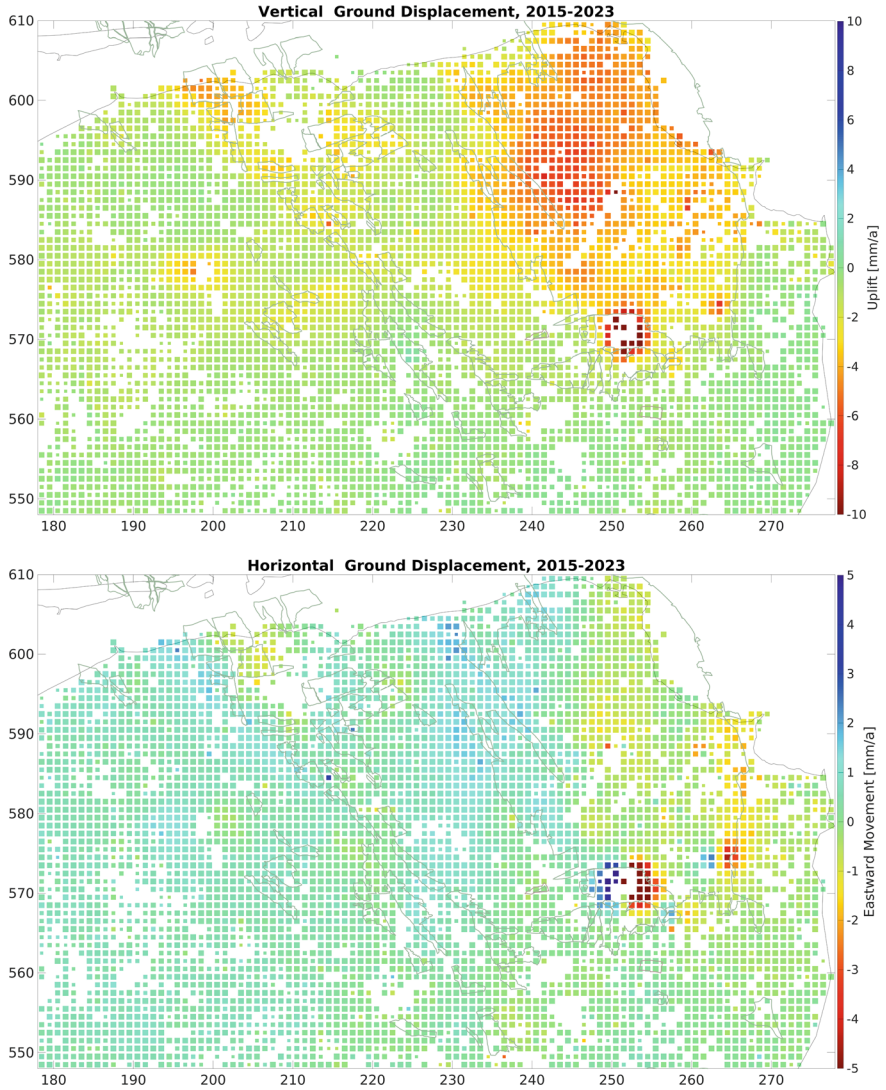


Fig. 2.9 Deformation from the decomposition of the ascending and descending Sentinel-1 time-series into vertical and horizontal components. The decomposition has been computed for all InSAR measurement targets representative for subsidence due to deep causes in areas of $1 \times 1 \text{ km}^2$. The size of the squares is an indication for the amount of InSAR measurement targets (NAM 2023)

$$\det(Q_{\text{PSI}} - \lambda Q_{\text{lev}}) = 0. \quad (2.5)$$

Eigenvalues less than one indicate that the precision of PSI is better than the precision of leveling, while eigenvalues larger than one indicate that the precision of leveling

is better. The best and worst precision are indicated by the smallest and largest eigenvalue respectively. The corresponding eigenvector represents the direction in the parameter space in which the precision corresponding with a certain eigenvalue is obtained.

2.2.5 Integrated Geodetic Reference Stations (IGRS)

In the period 2018–2021, 30 Integrated Geodetic Reference Stations (IGRS) have been placed in the northern part of the Netherlands. The IGRS stations (designed by Delft University of Technology) consist of a GNSS receiver, two InSAR corner reflectors (for ascending and descending tracks) and several levelling bolts, all mounted on a single (deeply) founded monument (Fig. 2.10). The IGRS form a unique geodetic reference network, since they unambiguously combine multiple measurement techniques, the measurements of which refer to the same deformation regime(s). The accuracy of the measurement techniques can be cross-validated directly. Also, spatially-dependent biases and noise can be assessed and mitigated using an IGRS network.

The IGRS stations were placed as part of the ‘Study and Data Acquisition Plan Induced Seismicity in Groningen’ (NAM 2016) and support minimizing subsurface uncertainties and optimizing future subsidence predictions. Density and locations of the IGRS stations have been chosen such that the areas with the largest uncertainty in subsurface behaviour are captured (e.g. areas with potential aquifer depletion that do not contain wells).

2.3 Geodetic Deformation Analysis Methodologies

Starting with philosophical considerations, this section describes the evolution of geodetic deformation analysis methodologies through time.

2.3.1 Philosophical Developments

Estimating subsidence in the Groningen area went through significant changes since the start of hydrocarbon production. In concert with technological and methodological developments, there has been a shift in the philosophy of monitoring land deformation.

At the start of the production, leveling was the only feasible geodetic technique applicable for monitoring the expected land subsidence. The philosophy of this can be characterized as an ‘application aware and aligned’ (AAA, or triple-A) approach. This implies that before starting the actual surveying, the ‘application’ was known,

Fig. 2.10 Integrated Geodetic Reference Station (IGRS), design by Delft University of Technology



in terms of its purpose and end-user, and the estimation procedure was aligned to that purpose. The purpose was to monitor and map the subsidence caused by the hydrocarbon production, at relevant temporal intervals, and the end-user was the state authority responsible for providing the producer its license to operate. The triple-A approach resulted in a network design to provide the required precision and reliability, the installation of benchmarks representative of the signal of interest, a temporal survey interval tuned to the expected inertia of the process, and output products in terms of tables and maps tuned to the expert eye of the end-user.

The effort needed to perform repeated leveling campaigns made a triple-A approach the only feasible one. The repeated leveling surveys took great efforts: they required experienced surveyors, were labor-intensive, costly, and posed practical risks e.g. by surveying along busy roads. The data adjustment to produce the final elevation differences (relative to a postulated reference benchmark) was labor intensive as well. Yet, the goals were clear, and the precision and reliability of the results were undisputed and satisfied pre-defined criteria. If measurement errors were made, the network design enabled their detection, and re-surveys were performed until the criteria were met. Up to this day, leveling provides the most precise and reliable estimates of height differences between benchmarks.

A consequence of the great effort required to provide leveling-based elevation difference estimates was that there was only one provider, and therefore only one final product. Even if undetected errors remained in the results, the absence of any ‘competing’ geodetic results over the same area imposed a responsibility on the

organizations providing the final results. This was obtained by involving independent parties who were generally considered to be well-respected and authoritative. The absence of competing results also implied a ‘what-you-see-is-what-you-get’ constraint for the end-user. Even though results may be disputed, the survey could not immediately be repeated only because of interpretation disputes.

Leveling provides campaign-style results—‘per-epoch’ in geodetic jargon—of adjusted height differences between points in a set of benchmarks. A subsequent leveling campaign would repeat this procedure over the same benchmarks and produce a new set of adjusted height differences. The tabulated sets of adjusted height differences over several epochs, known in Dutch as ‘differentiestaten’, could subsequently serve as input for the estimation of elevation-difference-changes. If one of the benchmarks was postulated (forced in the computations) to be of constant elevation, this would lead to elevation-changes per benchmark, relative to the reference benchmark. This way, the actual arbitrary elevations of the physical benchmarks are eliminated, and for each benchmark a time history of elevation-change could be established, starting at zero for the null-survey.

One disadvantage of the per-epoch adjustment is that a benchmark that was subject to displacement driven by mechanisms other than the hydrocarbon production would indeed satisfy the per-epoch adjustment criteria, but would not be representative for the AAA-goal that was limited to the subsidence due to the hydrocarbon production. This is known as the idealization accuracy, the degree to which an estimation represents the unknown signal of interest. The estimate of the elevation-change of the benchmark may be of high-precision, but it may be poorly linked to the signal of interest. It became clear that this problem is interpretation-related, and exceeds the discipline of geodesy only. It also stressed the crucial importance of a-priori network design, i.e., to establish benchmarks that are solely sensitive to the signal of interest.

As more leveling epochs were acquired, a new challenge appeared. Reservoir and geomechanical engineers could model the relationship between hydrocarbon production and subsidence, which was required to provide a prediction of future subsidence based on a particular production scenario. It is evident that while producing the Groningen field, and with a continuous feed of empirical data, knowledge about the mechanics and behavior of the field increased over time. In an ideal scenario, geodetic estimates of subsidence would remain detached from those models. In that way, the predictions of the models could a-posteriori be compared to the geodetic ‘evidence’, and an independent quality assessment of the model predictions would be enabled. In essence, one could view the geodetic results as ‘arbiter’ to decide on the quality of the models. In reality, the geodetic subsidence estimates indeed formed crucial input for establishing the models, and the models were not developed blindly of the geodetic estimates. Consequently, the geodetic estimates served as ‘team-player’ instead of independent arbiter. While it is clear that a detached, independent relationship between geodesy and geomechanics would be preferable conceptually, it is also clear that in the aim to produce realistic geomechanical models use is made of all relevant information available, including geodetic information. However, it required scrutiny and critical evaluation to avoid misinterpretation or circular argumentation.

While the discussion above discusses the one-way influence of geodesy on geomechanics, it is important that it is in effect implicitly a two-way influence. In the a-priori design of the measurement network, including benchmark positioning, benchmark density, benchmark foundation, and temporal repeat survey frequency, use needs to be made of physical information of the process. This includes the spatial dimensions and position of the reservoirs, the expected extension of potential subsidence broader than the reservoir, and the spatial and temporal smoothness of the expected subsidence signal. Thus, also in the direction from geomechanics to geodesy, exchange of information is crucial and inevitable.

In this arbiter versus team-player dispute, it became clear that the former cannot be sustained. It is both not possible and not desirable to keep geodesy and geomechanics apart in order to create an artificial ‘blindness’ in the comparison between both. The team-player model proved to be the only model that is practically feasible and desirable. The consequence of this conclusion is that, e.g., the hailed approach of ‘confrontation between data and model’, needed to be revisited. The current paradigm has therefore shifted to ‘transparency and refutability’. For the geodetic subsidence estimates, it needs to be both transparent and explicit which assumptions were made in the estimation procedure, and which contextual (including geomechanical) information was used. Likewise, geomechanical models and model predictions need to be accountable for the geodetic information that was used as their input. The transparency and refutability conditions ensure that it is possible to question the approaches followed, propose alternatives, and evaluate them on their own merits.

The advent of new geodetic technology and methodology such as GNSS and InSAR imposed new philosophical challenges. GNSS campaigns and later continuous operating stations largely follow a one-provider/one-product, triple-A approach, designed to the particular application with a well-defined end-user. An a priori network-design of station positions, optimized monumentation and foundation, ensured a close relation to the signal of interest. In terms of output, and similar to leveling, tabulated position (hence including elevation) changes over time could be produced for each station. In comparison with leveling this would be with less spatial density, but high temporal sampling, even though the latter would not be needed for the main subsidence signal of interest.

InSAR proved to be a game changer, not only technically but also philosophically. Effectively, the ‘surveying data’ were already available *before* the identification of the geodetic objectives in Groningen, and independent of their purpose, end-user, or applications. InSAR information products, to be interpreted as subsidence maps, could be created in an ‘application-agnostic’ (AA, or double-A) approach. This implies that it is possible to create a product even without knowing for which purpose it will be used and who will use it. Moreover, instead of a one-provider/one-product combination, aimed for one end-user, the availability and accessibility of the source satellite data enables many providers (both professional as well as laymen) to create many different products (relevant or non-relevant), for the same area of interest and based on the same source data. Different choices in the InSAR parameter estimation,

such as ambiguity resolution, atmospheric phase mitigation, and scattering thresholds, would lead to an infinite number of different products. Without knowledge of the final application, any AA-product can be considered as sub-optimal. Moreover, due to the relative ease with which InSAR products are created, in combination with increased pressure from society for open-data, many InSAR information products are accessible for many end-users, but not necessarily tuned to the level of expertise of each end-user. For the Groningen area, the fact that there are currently many different subsidence results available creates a new problem: which result should be trusted, how reliable is a product, and why do the results differ? It also creates the possibility of selective-shopping: preferring a result that supports potential pre-existing expectations or the interest of a particular stakeholder over a result that refutes this position. In geodesy, this is considered unacceptable.

Moreover, especially for InSAR one can distinguish a ‘tripartite nature of causality’, i.e., the result is caused by the particular interaction of three elements: the input data, the method to produce results, and the human operator performing or initiating the production of the results. A change in one of these three, while keeping the other two fixed, will cause a different result. For example, a different operator may make different choices for selecting certain thresholds or choosing particular filtering approaches. Different software packages are based on different premises and have different approaches for parameter estimation. The inclusion or exclusion of particular SAR acquisitions will induce differences in the final results.

Yet, while many InSAR products are application-agnostic (AA), and consequently sub-optimal, the SAR data can also be used to create application-aware and aligned (AAA) InSAR information products, with associated quality assessments. The equivalent of pre-survey geodetic network design of leveling and GNSS has then shifted to an a-posteriori network design. In essence, the challenge is to take advantage of the abundance of ‘survey-data’ to design a benchmark (i.e., scatterer) selection and parameter estimation approach that suits the conditions of the pre-defined application, and the known end-user of the products.

In terms of benchmark selection, the equivalent of selecting well-monumented, i.e., deep-founded, structures to establish a physical leveling benchmark is to find suitable radar scatterers a posteriori. These scatterer benchmarks are preferably accepted to be representative, i.e., only sensitive to, of deep causes of surface displacement. Alternatively, for benchmark scatterers whose displacement are susceptible to a cumulative range of driving mechanisms, these mechanisms need to be disentangled. For both approaches, the network design and analysis procedure is performed a posteriori.

The equivalent of the experienced surveyor and geodesist for the survey and its design, respectively, has shifted to the InSAR-geodesists performing their activities enabled by existing data. Similar to the surveyor, professional training, experience, and application-awareness are the best guarantees for creating an optimal result in a triple-A approach.

The final AAA-products are tailored to a specific end-user, with a known level of experience. Providing multi-interpretable or ambiguous results may not be a problem for experts who can weigh the results and interpret them wisely. However, for

laymen the same product would be confusing at best, or lead to disappointment or disengagement at worse. This is a, perhaps, inevitable consequence of the current commoditization of geodetic data, methods, and products.

As technology, methodology, and society advance, so must geodesy advance in a more philosophical perspective. Professional geodetic training that is attuned to these developments is therefore more important than ever, but a challenge to accomplish.

2.3.2 *Delft Adjustment and Testing Theory*

In the first decades in which leveling campaigns were carried out, Delft adjustment and testing theory has been applied to compute leveling height estimates. In the design of the leveling network, the following was taken into account:

- Usage of existing benchmarks in buildings with heights already published by Rijkswaterstaat in the NAP register.
- Selection of reference benchmarks that are assumed stable, meaning that they are not subject to deformation caused by gas extraction.
- Usage of leveling loops to create redundancy and be able to detect measurement errors.

Rijkswaterstaat nowadays publishes the specifications for secondary leveling campaigns for maintaining the NAP datum (Rijkswaterstaat 2023).

Both first phase and second phase adjustment computations were carried out. In the first phase, a free network adjustment was computed. In the second phase adjustment computations, the heights of a number of stable reference benchmarks were kept fixed. Statistical measures on the accuracy of the height estimates were published as well. These stem from the work of Prof. Baarda on testing theory (Baarda 1968).

In geodesy, internal and external reliability are distinguished. A measure that is related to internal reliability is the ‘Minimal Detectable Bias’ $|\nabla|$, which is the measure of a model error that can be detected with a certain probability.

$$|\nabla| = \left(\frac{\lambda_0}{c_y^T Q_y^{-1} Q_\varepsilon Q_y^{-1} \nabla_y} \right)^{1/2}, \quad (2.6)$$

where c_y is a $m \times 1$ vector that specifies the model error, describing the internal reliability of H_0 with respect to H_A (alternative hypothesis).

The external reliability describes the influence of a model error ∇_y on the parameter estimates:

$$\nabla_x = (A^T Q_y^{-1} A)^{-1} A^T Q_y^{-1} \nabla_y, \quad (2.7)$$

where A specifies the functional relation between observations and unknown parameters and Q_y is the variance-covariance of the observations.

From 1972 onwards, subsidence is reported as height differences with respect to previously calculated NAP heights, in a so called ‘staat van periodieke verschillen’. Each benchmark gets a stability classification. Awareness that height differences can be caused by other deformation regimes, such as natural shallow compaction, water extraction and salt mining, is present.

A subsidence contour map is created based on the interpolation of the NAP height differences of leveling benchmarks. The usage limitations of this map are indicated, stating that the contour lines are affected by the density distribution of benchmarks and local effects of different deformation regimes.

For large leveling campaigns, it is acknowledged that subsidence can also occur during the leveling campaign itself (if spread over several months).

With the measurements of multiple leveling campaigns becoming available, the stability of reference benchmarks can be tested. This leads to new set of reference points (van den Berg 1980).

2.3.3 *Geodetic Deformation Analysis (ScanDefo)*

In the 1990s, the application of the Delft adjustment and testing theory for subsidence monitoring was further extended by including deformation modeling (de Heus et al. 1994c, 1995; Verhoef and de Heus 1995; NCG 1995). Software for deformation monitoring was developed by the department of Mathematical Geodesy of Delft University of Technology, in collaboration with Rijkswaterstaat (‘Meetkundige Dienst’) and NAM. This software called ‘ScanDefo’ had a modular set up aiming for:

- adjustment and testing of single leveling campaigns,
- stability analysis of reference benchmarks,
- selection of the deformation model with the highest probability via hypotheses testing.

2.3.4 *Geodetic Spatio-Temporal Analysis (SuMo)*

Towards the year 2000, the awareness materialised that for an increased insight into subsidence, an integral analysis of all available measurements in space and time was required. Several challenges could not be met by analysing a series of individually adjusted levelling networks (Quadvlieg 2002b):

- Network configurations vary over time. Maintaining their density by replacing disappearing benchmarks does not remedy the decrease of benchmarks covering the full monitoring period. Quantifying subsidence since the start of gas production was limited to these benchmarks.
- The availability of stable reference points that are present in all epochs was limited.

- There was no statistical toolset in place to discriminate subsidence caused by hydrocarbon production from other deformation regimes and noise.

These shortcomings could be resolved satisfactorily by an integral trend-signal-noise approach that exploited spatio-temporal correlations to bridge the gaps between benchmarks in space and campaigns in time. Between 1998 and 2003 TU Delft developed the Subsidence Modelling (“SuMo”) software in cooperation with NAM. SuMo approximated ground deformation by a linear combination of ellipsoidal subsidence bowls growing with time (Houtenbos 2000; Kenselaar and Martens 2000a; Kenselaar and Quadvlieg 2001). This parametric model was complemented by a signal component that was computed at grid points through least squares collocation using a commercial off-the-shelf software, see Fig. 2.11. The full stochastic model discriminated three components:

- *Model noise*: spatio-temporally correlated signal that describes the deviation of the signal of interest from the idealised functional shape,
- *Point noise*: temporally correlated signal that describes autonomous behaviour of individual benchmarks and
- *Measurement noise*: uncorrelated signal that describes the uncertainty of the measurement itself at the level of observed height differences.

In this framework, the observations could be tested in a more sophisticated manner by considering different alternative hypotheses including observation errors, identification errors (observing the wrong benchmark in a specific epoch), generally deviating point behaviour (point test), autonomous linear behaviour of points and generally deviating epochs (epoch tests). Applying the B-method of testing (Baarda 1968), these hypotheses were used to iteratively adapt the functional and stochastic model until the overall model test was passed. At that stage, the SuMo software governed a model that could predict subsidence at any point in space and time, not limited to discrete benchmark locations and campaign epochs. It still required assumptions on stochastic parameters. For the point noise component a large scale calibration effort was made (Houtenbos and Kenselaar 2001), the outcome of which is still being used today.

2.3.5 *Geodetic Spatio-Temporal Analysis Using Geomechanical Models (SuRe)*

SuMo was a milestone in geodetic analysis of subsidence measurements, but its approach was questioned by geomechanicists, because the geometric approximation by ellipsoidal subsidence bowls did not allow for the complexity of subsurface mechanics and might introduce artefacts. On the other hand, an integrated dynamic deformation analysis that linked geodetic subsidence observations with their underlying geomechanical model was not possible with surface measurements

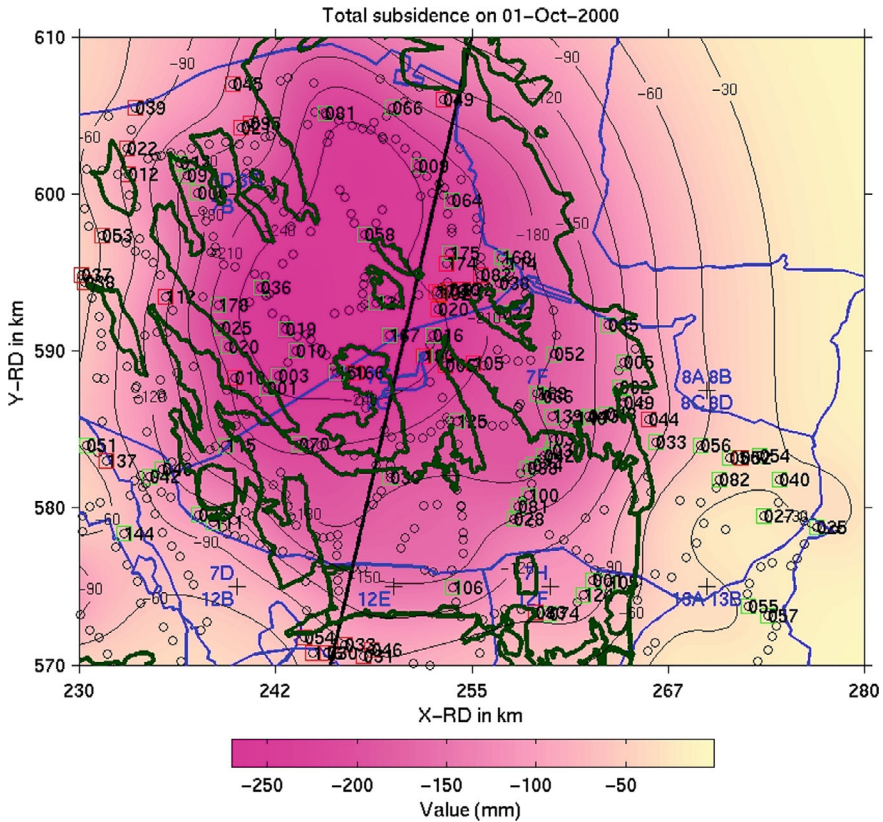


Fig. 2.11 Subsidence (mm) in 2000 above the Groningen gas field computed by SuMo (Quadvlieg 2002a)

as its only input (Kenselaar 2002). Extending both functional and stochastic model by subsurface observations was too complex an exercise to consider.

The next advancement leading to another milestone was the Subsidence Residuals ('SuRe') software developed by Houtenbos (2007) in the early 2000s. It adapted the basic concepts of SuMo but overcame two of its shortcomings: firstly, it did not approximate subsidence by a parametric model but rather used an a priori geomechanical prediction as input. This was removed as an a priori trend from the observations so that the software only had deal with the residuals. Secondly, SuRe was capable to calibrate the noise parameters by means of variance component estimation, making the stochastic model more objective and less dependent on expert judgement.

The set of alternative hypotheses was slightly modified. Observation errors, identification errors and autonomous linear behaviour of points were adopted from the SuMo framework and complemented by disturbances, sudden jumps in the time series of benchmarks between two epochs. The B-method was used to test the hypotheses

in comparison with the overall model test, re-estimating variance components in case the latter was rejected. Iterative testing and model adaptation was implemented in an automated data snooping loop.

The framework of SuRe provided the opportunity to statistically test geomechanical models as already proposed twenty years earlier (Pöttgens 1982). However, this was hampered by the poor a priori knowledge on the model noise component. Testing would require subjective expert judgement, because the overall model test could not be used to validate a geomechanical prediction and calibrate the corresponding model noise at the same time.

While the SuRe approach was recognised as state-of-the-art (TCBB 2008), the software has not led to a consensus on the estimation of subsidence from geodetic measurements in the multi-disciplinary community and across governmental authorities. It was deemed too complex and dependent on expert user input to adopt it as a broadly accepted standard. Geomechanics domain experts were mainly concerned about the bias imposed by the a priori geomechanical prediction. They also refrained from using the SuRe output as an input to their modelling to avoid an additional error source originating from ‘geodetic preprocessing’. Nevertheless, SuRe proved useful to produce subsidence maps directly based on geodetic observations. For this purpose, SuRe is still in use today as can be seen in Fig. 2.12.

2.3.6 *Integrated Geodetic Processing (IGP)*

Estimation of a deformation signal of interest from geodetic measurements continued to be a focus area in the next decade. As part of the ‘Study and Data Acquisition Plan Induced Seismicity in Groningen’ (NAM 2016), several geodetic studies were launched, among them ‘Integrated Geodetic Processing’ (IGP) (van Leijen et al. 2021).

The aim of Integrated Geodetic Processing is to apply the Delft school methods for adjustment and hypothesis testing on the integration of measurements from different techniques, using their full variance-covariance matrices in the stochastic model. Hereby, the final goal is to jointly estimate the spatio-temporally correlated deformation signal of interest, and provide its quality description. It is initially focussed on leveling, GNSS and InSAR measurements, but the Integrated Geodetic Processing software is set up in such way that measurements by other techniques, such as gravimetry, can be added as well in the future.

The geodetic measurement techniques used are complementary to each other due to their spatial density and coverage, temporal density and coverage, sensitivity (1D/2D/3D) and datum. Although this complementarity provides opportunities, it also brings challenges. First, measurements from different geometries need to be combined: deformation along the satellite look angle, along the vertical, with or without horizontal components (east, north, or along a component from the satellite

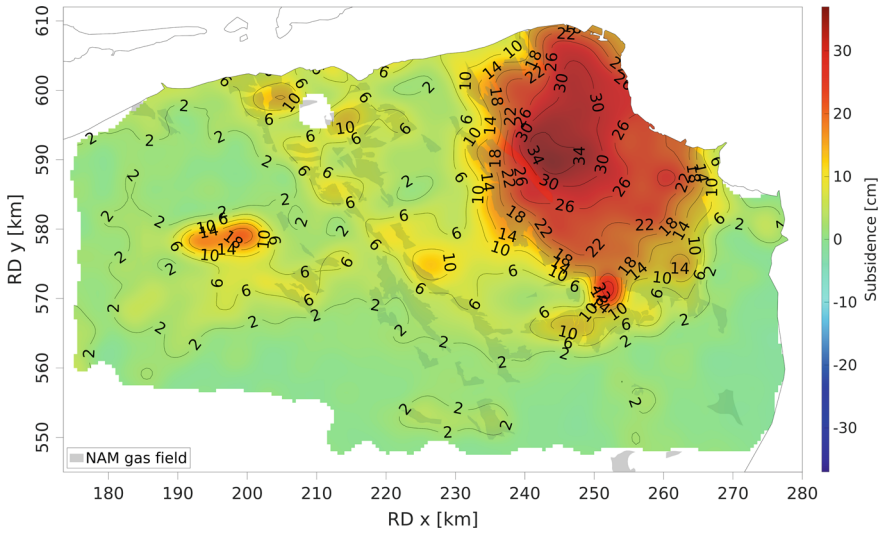


Fig. 2.12 Subsidence in the Northern Netherlands between 1964 and 2018 as predicted by SuRe based on levelling observations (NAM 2020, p. 52)

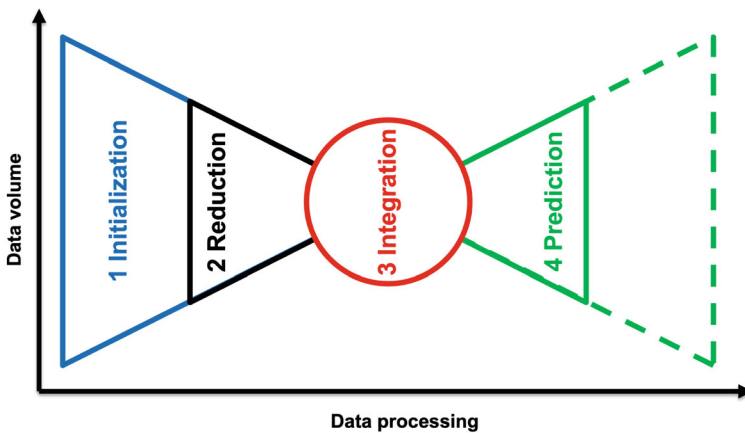


Fig. 2.13 Illustration of the Integrated Geodetic Processing workflow. The horizontal axis indicates the processing flow, whereas the vertical axis shows the data volume

viewing geometry). Secondly, in general measurement points are physically different, and the measurement epochs do not correspond. And third, as a result, the measurements may be sensitive to (the superposition of) different deformation regimes. Finally, potential differences between the geodetic datums are accounted for.

The IGP framework is based on four main processing steps: (1) initialization, (2) data reduction, (3) integration, and (4) prediction, see Fig. 2.13. In the initialization step, each dataset is pre-processed to account for certain technique-dependent

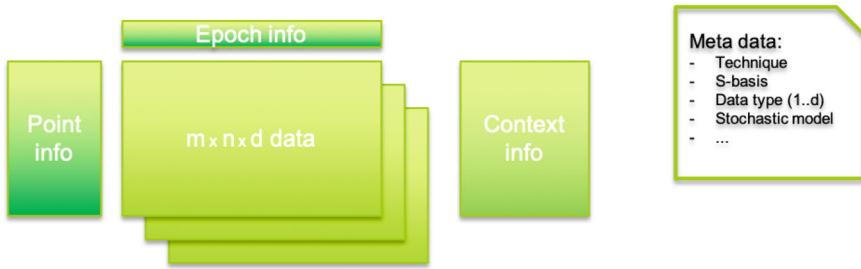


Fig. 2.14 The Space-Time Matrix (STM) data concept

error sources, such as benchmark identification errors in case of leveling data. Subsequently, the datasets are transformed into a common data format, the Space-Time Matrix (STM), see Fig. 2.14 (Bruna et al. 2021; van Leijen et al. 2021). The STM format contains the geodetic observations, the accompanying covariance matrix or model, point specific, epoch specific and contextual attributes, and metadata. The common STM format enables easy data manipulation in the rest of the IGP processing flow.

Regarding the stochastic models used, insights from recent studies were taken into account. In the period 2013–2017 the Long Term Subsidence (LTS) studies were carried out by NAM with multiple consortium partners (NAM 2017). The main goal of these studies was to develop a new confrontation workflow between geodetic data and (large sets) of physical subsidence models (combinations of reservoir scenarios and geomechanical models), including the computation of confidence intervals. The LTS studies also resulted in improved stochastic models for leveling and GNSS, see for example Fig. 2.15. Additionally, the methodology developed by Delft University of Technology to construct a full variance covariance matrix for InSAR, also applicable to reduced datasets in time and space (Samiei-Esfahany 2017; Samiei-Esfahany et al. 2020, 2021) is applied. When using this methodology in practice however, it appeared that it needed to be slightly adapted to avoid singularities.

Once the various geodetic datasets are available in STM format, a data reduction is applied. This reduction is needed since especially the number of points in the InSAR data, and the number of epochs in case of continuous GNSS stations, is too large for direct integration. The data reduction is based on the concept of ‘evaluation points and epochs’. The set of evaluation points is based on the existing leveling and GNSS points, and further densified by a user-defined grid for the reduction of the InSAR datasets, as shown in Fig. 2.16. For each of the evaluation points and epochs, corresponding observations among the various datasets are identified, using certain distance and time thresholds.

In the integration step, an estimation and testing procedure is applied based on the linked observations. Depending on the sensitivity of the observations, e.g., vertical, radar line-of-sight or 3D, transformation parameters, offsets and displacement time

series are estimated in the East, North and Up direction. In addition, the observations are tested to evaluate whether the hypothesis holds that they describe the same deformation signal. The tests are done on point, epoch and full dataset level. Once the tests are accepted, after removal of outliers, a new dataset in the STM format is created with the estimated displacement time series, with its full covariance matrix.

Fig. 2.15 Idealisation noise model estimated from an onshore double-difference (in space and time) leveling dataset, evaluated for standard deviations of double-differences covering spatial distances of 0, 1, 5 and 20 km, and different time intervals. The dashed lines are including leveling measurement noise. From NAM (2017)

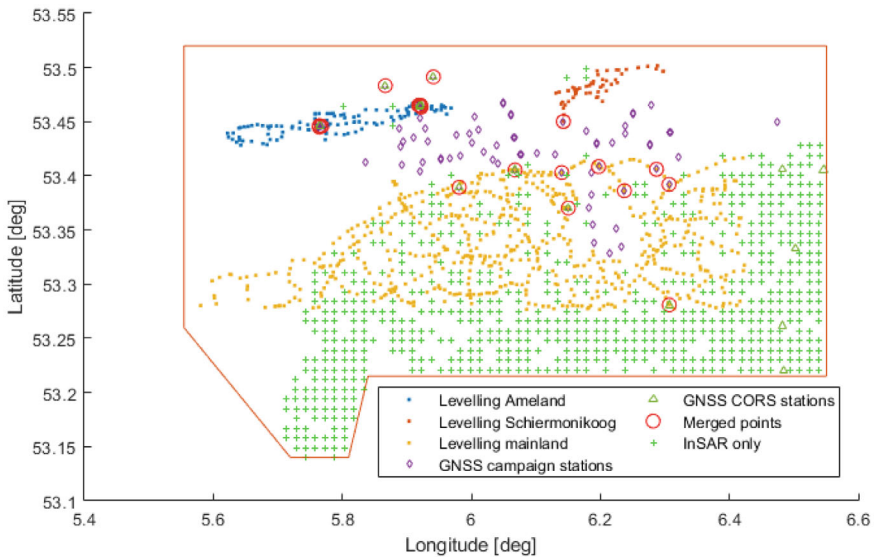
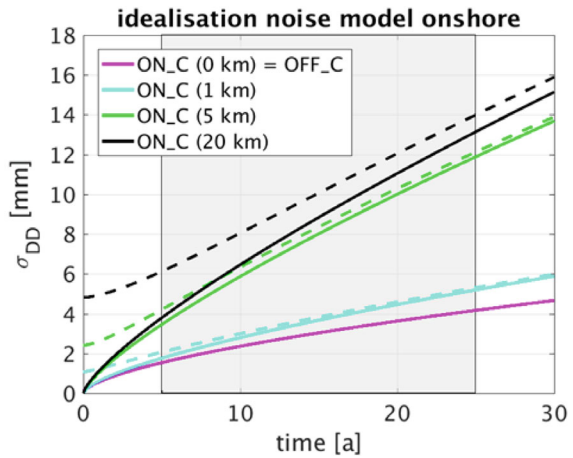


Fig. 2.16 Example of the distribution of evaluation points for the Wadden Sea area. The evaluation points are based on benchmarks observed by three leveling networks, GNSS continuous and campaign stations, together with a densified grid from InSAR. Nearby benchmarks from different networks are merged into a single evaluation point

The final step in the IGP workflow is the prediction of displacements at any desired location and time. Here, the concept of Best Linear Unbiased Prediction (BLUP) is applied (Teunissen 2007). Hereby, the system of equations for the estimation of the deformation signal can be formulated as

$$\underline{y} = Ax + \underline{s} + \underline{n} \quad ; \quad Q_y = Q_{ss} + Q_{nn}. \quad (2.8)$$

where the design matrix A describes the functional relation between the observations y and the unknown deformation parameters x . The part of the deformation signal that is stochastically modeled is denoted by s . The measurement noise is represented by n . The total variance-covariance matrix Q_y is the sum of the matrices describing the stochastics of the signal Q_{ss} and noise Q_{nn} .

Trend, signal and noise can be separated by

$$\hat{\underline{x}} = (A^T(Q_{ss} + Q_{nn})^{-1}A)^{-1}A^T(Q_{ss} + Q_{nn})^{-1}\underline{y}, \quad (2.9)$$

$$\hat{\underline{s}} = Q_{ss}(Q_{ss} + Q_{nn})^{-1}(\underline{y} - A\hat{\underline{x}}), \quad (2.10)$$

$$\hat{\underline{n}} = Q_{nn}(Q_{ss} + Q_{nn})^{-1}(\underline{y} - A\hat{\underline{x}}). \quad (2.11)$$

To apply the trend-signal-noise model to estimate deformation at locations and points of time without observations, the system of equations is written for the unobservable y_0

$$\underline{y}_0 = Ax + \underline{s}_0 + \underline{n}_0. \quad (2.12)$$

The unobserved deformation signal can then be predicted by

$$\hat{\underline{s}}_0 = Q_{s_0s}(Q_{ss} + Q_{nn})^{-1}(\underline{y} - A\hat{\underline{x}}), \quad (2.13)$$

where

$$\hat{\underline{n}}_0 = 0 \quad (2.14)$$

and Q_{s_0s} describes the stochastic relation between the signal at the observation and prediction points and epochs. The total displacement at a certain point and epoch then becomes

$$\underline{\hat{y}}_0 = A_0\hat{\underline{x}} + \hat{\underline{s}}_0. \quad (2.15)$$

To assess the precision of the prediction, the variance-covariance matrix of the prediction error is computed as

$$P_{\hat{\epsilon}_0\hat{\epsilon}_0} = Q_{y_0y_0} - Q_{y_0y}Q_{yy}^{-1}Q_{yy_0} + (A_0 - Q_{y_0y}Q_{yy}^{-1}A)Q_{\hat{x}\hat{x}}(A_0 - Q_{y_0y}Q_{yy}^{-1}A)^T. \quad (2.16)$$

Hereby, a prediction including precision description is obtained.

2.4 Future Outlook of Geodetic Deformation Monitoring

In recent years, scientific research has further investigated movements in the shallow and deep subsurface. An example is the Living on Soft Soils (LOSS) programme (Stouthamer et al. 2020), with dedicated research covering measuring subsidence, subsidence mechanisms, the physical and economical impact of subsidence, and governance approaches in an integrated way (Erkens and Stouthamer 2020). Subsidence mechanisms are studied with an increasing level of detail, as millimetric changes (per year) matter for e.g. sea level rise monitoring and greenhouse gas emissions from peatlands (van Asselen 2020; Candela et al. 2020; Kooi and Erkens 2020; Koster et al. 2020; Janssen and Stouthamer 2022; de Wit 2022; Lexmond et al. 2024). Geodetic techniques such as leveling, InSAR and GNSS play an important role in measuring subsidence. Conroy et al. (2022, 2023) describe the advances in InSAR for monitoring shallow deformation processes in rural areas. Geodetic processing and testing techniques are evenly important to assure the correct precision and reliability of deformation estimates.

There are two deformation phenomena specifically that cause movements in (sub-)millimetric magnitude ranges: surface deformation caused by geological processes (e.g. plate movements, isostatic movements), and deformation of subsurface layers (e.g. shrinking and swelling of clay layers). Here, geodetic deformation analysis has some key discriminators:

- Geodetic adjustment and testing theory results in metrics that assess the precision and reliability of the deformation estimates, and hence can indicate to which extent physical parameters can be estimated with a certain level of significance.
- The concept of ‘idealisation precision’ is well embedded in geodetic deformation analysis: do the measurement targets represent the deformation signal of interest? In case of a superposition of deformation signals, solid solutions have been investigated exploiting the stochastic behavior of deformation signals (using the theory of y^R variates (Teunissen 2000a), Variance Component Estimation (Verhoef 2004; Teunissen and Amiri-Simkooei 2006; Houtenbos 2007)) and making use of knowledge on physical properties of the measurements targets in the geospatial domain (e.g. foundation depth).
- The understanding of geodetic datums and coordinate reference systems is key to assess the limitations and potential of geodetic deformation monitoring techniques. For example, the usages of ETRF2000 for GNSS results in vertical movements of -0.9 mm/year, which are due to choices in the definition of the reference system. It is counter intuitive, but in deformation monitoring in the Netherlands, ITRF is preferable for the vertical component (van der Marel 2020).
- Advanced research has been done to estimate (and remove) signal in the measurements that is unrelated to deformation of the subsurface. A conservative approach is used here: only signals that are physically explainable and do not have spatio-temporal characteristics similar to the deformation signal of interest, are removed. This implies that a lower accuracy is preferred over a systematic bias in the deformation estimates (van der Marel 2020).

Also other techniques have been exploited to retrieve insight in the deformation regimes that are incorporated in the deformation estimates. Verberne et al. (2023) models the soil composition and the groundwater level of the shallow subsurface and calibrates these models with geodetic data such as InSAR.

Methodologies which are able to estimate multiple deformation regimes from geodetic deformation estimates become increasingly important because of societal developments:

- Due to the energy transition, new energy sources are exploited (such as geothermal heat), and subsurface storage of matter (such as carbon dioxide) is increasing.
- To achieve the climate goals, dedicated groundwater level management is key, as well as a precise and reliable computation of the effect on subsidence and uplift at ground level. This is both important to control green house gas emissions, as well as to assess the impact of sea level rise.

Regarding the estimation of sea level rise, geodetic deformation analysis can also play a role to further improve its estimation. Currently, tidal stations are connected to the Dutch network of NAP benchmarks by means of periodic leveling measurements, via a bolt in a founded pole near the tidal station, or a bolt in the wall of the tidal station building (Honingh et al. 2021). The Dutch NAP network however does not have as primary goal high accuracy deformation monitoring. It is designed for water management and as reference network for construction activities. NAP heights are estimated in a constrained way using a number of fixed reference benchmarks. NAP heights of reference benchmarks are only adapted if observed movements exceed a certain threshold, and only after regional leveling campaigns (interval 5–10 years). Computed spatio-temporal height differences from NAP heights are less accurate than if they would have been estimated in a spatio-temporal geodetic analysis using the measured height differences between benchmarks. There is also an effort to increase GNSS monitoring for sea level rise computations (Strijker et al. 2020).

With climate change driving towards micro management of subsidence in the Netherlands in an increasingly complicated environment as well (e.g. new energy sources exploiting the subsurface), the application of geodetic deformation analysis is more relevant than ever. It becomes even more relevant, when realizing that in the past, mitigating measures resulting from subsidence were primarily limited to measures related to water management in the Netherlands (e.g. heightening of dikes, height of bridges). Climate change, however, leads to more extremes in the shallow subsurface as well (e.g. effects of droughts), and hence structural stability monitoring of objects (buildings, infrastructural works) becomes increasingly important too. Geodetic measurement, processing and analysis techniques hence are key contributors to a safe and healthy future environment.

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