NAM

Gravity monitoring of the Groningen gas field 2015

Quad Geometrics, Ola Eiken

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Editors Jan van Elk & Dirk Doornhof

General Introduction

The reservoir engineering model for the Groningen field is continuously improved and updated with the latest data available (Ref. 1 and 2). The most current update of the model for Winningsplan 2016, has been calibrated with reservoir pressure data, compaction data and wellhead pressure data (Ref. 3, 4 and 5).

Especially in areas away from the existing wells reservoir or wellhead pressure data is not available. To further calibrate the model especially in these areas a gravity survey was conducted. An earlier gravity survey was conducted 1978, and repeated in 1984, 1988 and 1996. The gravity survey described in this report was conducted in 2015. From the changes in the measured gravity, mass displacement in the subsurface can be deduced. This potentially provides additional constraints on the reservoir model.

References

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Organisation	**Quad Geometrics**	**Organisation**	NAM
Place in the Study and Data Acquisition Plan	Study Theme: Groningen Reservoir Model Comment: The reservoir engineering model for the Groningen field is continuously improved and updated with the latest data available (Ref. 1 and 2). The most current update of the model for Winningsplan 2016, has been calibrated with reservoir pressure data, compaction data and wellhead pressure data (Ref. 3, 4 and 5). Especially in areas away from the existing wells reservoir or wellhead pressure data is not available. To further calibrate the model especially in these areas a gravity survey was conducted. An earlier gravity survey was conducted 1978, and repeated in 1984, 1988 and 1996. The gravity survey described in this report was conducted in 2015. From the changes in the measured gravity, mass displacement in the subsurface can be deduced. This potentially provides additional constraints on the reservoir model.		
Directliy linked research	(1) Reservoir engineering studies in the pressure depletion for different production scenarios. (2) Subsidence and compaction studies.		
Used data	New Measurements.		
Associated organisation	NAM		
Assurance	Quad Geometrics and NAM		

QUAD GEOMETRICS

Gravity monitoring of the Groningen gas field 2015

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April 27th 2016
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1 Summary

High-precision gravity surveys have been carried out repeatedly above the Groningen gas field, with initial 23 stations measured in 1978, repeated in 1984, 1988, 1996, and extended to a 98 station survey in 2015. A particular challenge in 2015 was to find or identify the old locations. For 11 old stations were new sites with easier access defined nearby, and gravity values were transferred. Infill sites have mostly been placed on either seismic stations, on asphalt covered entrance roads to NAM plants or at church entrances. Three reference stations outside the field were included in the survey grid, of which Westerbork and Aurich have previous absolute measurements.

Data acquisition took place from 13th to 27th September 2015, with 309 measurements at the 98 stations, using 3 CG5-sensors equipped in gimbal frames. All stations received at least 3 visits. Fourteen relative measurements were made at the central reference station in the Overschild windmill, where also absolute gravity was measured with 1.8 μGal precision. Two reference gravimeters centrally in the area recorded earth tides during the survey, and the model agreed within 1 μGal with the data.

Scale factors have been calibrated in the San Diego and Westerbork-Monschau ranges prior to the survey, in the reference stations in Westerbork, Overschild and Aurich during the survey, and by analyzing unit differences of all the survey data. Final uncertainty (standard deviation) is estimated to 3.3 x 10^{-4}, higher than formal uncertainties from the calibration ranges suggest.

Transfer measurements were done in the days prior to and after the main survey. Nearly all station pairs have a gravity measurement precision better than 3 μGal. Much larger uncertainties arise from height changes and related near-surface mass changes; up to 14 μGal for some sites.

Re-processing of the 1978, 1984 and 1988 surveys were done from supplied raw readings. Linear daily drift-segments were mostly applied in the corrections. For the 1996-survey, 3 different readings were provided for each measurements, showing a stability of about 3 μGal. Measurement repeatabilities are for the 1978-1996 surveys: 10, 7, 6 and 6 μGal, and station uncertainties are on average 5.2, 3.4, 3.1 and 4.3 μGal.

The 2015-data consists of 20-minutes records sampled at a 6 Hz rate. Average time-series stability was better than 2 μGal for all units. The final drift segment definition has from 10 to 12 measurements per drift coefficient. In addition to linear and cubic drift, a periodic (diurnal) drift component have been found, probably caused by day-night temperature variations. Recovery corrections have been applied. Final unit repeatabilities range from 2.5 to 4.7 μGal for the units, and measurement repeatability is 1.7 μGal, after giving units 13 and 10 highest weight. Station uncertainties (standard deviation) are on average estimated at 1.1 μGal.

Ground-water level is controlled by man in the Groningen area. Data on water levels in ditches, canals and groundwater wells suggest time-lapse gravity variations are less than 10 μGal, although the understanding of the moisture and water transport through the soil is lacking at the moment. More data exist, and a better understanding of the hydrology variations and thus gravity corrections can be gained from further development work and analysis of data. This is beyond the scope of this report, but is recommended to improve precision in future repeats.

During the initial time-lapse analysis, scale factors in the pre-2015 surveys have been adjusted, based on minimizing residuals at reference stations. Uncertainty in the subsidence data, provided by NAM, is estimated at 1.5 cm. Ten stations situated south of and along the western rim of the field have modeled gravity changes less than 4.7 μGal in the time-span from 1978 to 2015, and have been

defined as reference stations for the time-lapse analysis. These suggest an average time-lapse uncertainty of 9 μGal standard deviation, after 20% of the measurements were omitted. Formal uncertainties in the zero-level range from 2.3 to 5 μGal. The 1984 and 1988 surveys show larger average gravity reductions over the field than expected, well above the zero-level uncertainty. This distinct observation remains unexplained. For the other vintages, average gravity reductions are as expected. The time-lapse results from individual stations, after omitting two data points (outliers), show mostly gravity decreases after correcting for subsidence. Only station #9 Ten Boer shows gravity increases, and these are consistent with the modeled gravity changes. Between 1996 and 2015, stations #11 and #12 shows more than 30 μGal larger decrease than in the model. From 1978 to 2015, the neighboring stations #13, #15 and #17 show 17-20 μGal larger observed than modelled gravity reductions. Mis-match between observations and model is on average 14 μGal, with error contributions from noise and model estimated to be of about equal size. Precision of future monitoring compared to 2015 is expected to be significantly better, with detectable signal/noise ratios after about 3 years.

2 Introduction

High-precision gravity surveys have been carried out repeatedly in the Groningen area in 1978, 1984, 1988, 1996 and recently in 2015 (Table 1). The initial network of 23 stations increased to 27 stations in 1996 (Table 2), and was strongly densified to 98 stations in 2015 (Figure 1). Results from the 20th century surveys have previously been published in Strang van Hees (1980), Bilker (1996), Gelderen et al. (1998) and Gelderen et al. (1999), with a gas depletion signal being reported. These data have been reprocessed by Quad Geometrics in 2015-2016, together with processing of the 2015 gravity data and the subsidence data received from NAM. The results are presented in this report, together with descriptions of stations and the 2015 data acquisition.

All data related to the 2015 acquisition and processing, including this report, is stored on an external hard disk, and handed over to NAM. For safety, a copy will also be kept by Quad Geometrics Norway.

Year	Start date	End date	Survey duration [days]	Number of stations	Total number of measure-ments	No of measure-ments at reference station #2 Gasselte	No of remote calibration measurements	No of measurements in Groningen area, excluding Gasselte, Assen, Westerbork and Aurich
1978	September 25th	October 13th	18	22	113	27	6	80
1984	June 6th	July 3rd	27	29	140	21	28	91
1988	May 30th	June 9th	10	24	109	16	3	90
1996	February 6th	February 17th	11	26	114	2	0	107
2015	September 13th	September 27th	14	98	309	3	3	294

Table 1: Key numbers for the time-lapse gravity surveys of the Groningen field.

No	Station name	1978	1984	1988	1996	2015
1	Pijnacker		10			
2	Gasselte NHChurch	27	21	16	2	3
3	Annerveen	3	4	4	3	3
4	Tussenklappen	4	3	4	4	3
5	Roode Til	3	5	4	3	3
6	Haren	5	5	6	4	3
7	Kooipolder	5	6	6	2	3
8	Groningen Oosterpark	9	11	5	2	3
9	Ten Boer	6	5	4	4	3
10	Schildmeer	4	5	5	3	3
11	Ten Post	3	5	4	3	3
12	Delfzijl	3	2	4	3	3
13	Stedum	4	5	3	6	3
14	Winsum	4	3	4	6	3
15	Middelstum Church	3	4	3	3	3
16	Leermens	3	3	3	2	3
17	Garsthuizen	3	3	3	3	3
18	Bierum	3	4	3	3	3
19	Uithuizermeeden-K	4	3	3	4	3
20	Eenrum	3	1	3	3	3
21	Usquert	3	2	3	4	3
22	Uithuizermeden	4	2	3	3	3
23	Maastricht		1			1
24	Eindhoven		3			
25	Den Haag		5			
26	Utrecht-Hom.	6	2			
27	Utrecht-Stat.		3			
28	Vaassen		1			
29	Zwolle		2	5		1
32	Winschoten NS			4	2	
33	Assen NS				3	3
34	Wagenborgen				3	3
35	Gasselte-OM				2	3

Table 2: List of all pre-2015 stations, with number of visits in each survey.

Figure 1: Map of survey area, with all stations measured in 2015 marked as colored droplets with station numbers. Previously measured stations in red, new reference stations in gray and new infill stations in green, orange and yellow.

All stations are listed in Table 3. The pre-2015 stations are numbered 2-35. For several of these, a new site with easier access was defined adjacent to it (within about 100 m), and 500 has then been added to the original number. The gravity difference between these pair of stations were measured in 2015, as described in Chapter 12 (transfer measurements). Of the 98 stations, nine are at church entrances (six of these are new stations), two at railway stations (both measured prior to 2015), two are OM's (Ondergrond Mark's) and two are old stations at public sites. Six sites remain inside the fence of NAM (Nederlandse Aaardolie Maatschappij) sites, after eight stations were moved outside of the fence in the 2015 transfer measurements.

Twenty-one of the pre-2015 stations (#2-22) span the area of the gas field and have been measured in all surveys (Table 2). In addition, stations #30 & #32-35 near the Groningen field were measured in the later surveys. Stations #1 & #23-29 are 100-300 km further south and belong to the gravity network of the Netherlands. These seven stations were all measured in 1984, and also #26 Utrecht in 1978 and #29 Zwolle in 1988. These data can provide network ties and scale factor calibrations.

No	Station name	Latitude (WGS84)	Longitude (WGS84)	RDX	RDY	Description
2	Gasselte church	52.972196	6.787937	249094	554823	Church entrance
3	Anneveen	53.088200	6.783000	248512	567725	NAM plant, inside house. Access 9-17, notification to NAM the day before.
4	Tussenklappen	53.155100	6.870200	254201	575285	Gras field inside NAM plant
504	Tussenklappen	53.154916	6.870064	254192	575265	Nail, red circle in asphalt, outside fence of NAM plant
5	Roode Til	53.192800	6.929000	258044	579563	NAM plant, nail, red circle in asphalt. Access 9-17, notification to NAM the day before.
6	Haren	53.183	6.64345	238980	578102	Inside observation hut
506	Haren	53.182920	6.644030	239019	578093	Nail, small red circle in asphalt
7	Kooipolder	53.207600	6.762900	246912	580985	Fresh asphalt inside NAM site.
507	Kooipolder	53.20759	6.763034	246921	580984	Nail, red circle in asphalt. Outside fence of NAM site.
8	Groningen Sint Fraciscuskerk	53.228530	6.577090	234460	583093	Church entrance
9	Ten Boer	53.259570	6.643590	238841	586622	NAM plant, nail, red circle in asphalt. Access 9-17, notification to NAM the day before.
10	Schildmeer	53.282300	6.865100	253569	589432	Gras field inside NAM plant.
510	Schildmeer	53.282249	6.865310	253583	589427	Nail in asphalt. Outside fence of NAM plant.
11	Ten Post	53.299300	6.745000	245524	591166	Gras inside NAM plant
511	Ten Post	53.299269	6.743917	245452	591161	Nail, red circle in asphalt. Outside fence of NAM plant.
12	Delfzijl	53.303500	6.971900	260639	591943	Gras inside NAM plant.
512	Delfzijl	53.30354	6.97186	260637	591947	NAM plant, nail, red circle in asphalt. Access 9-17, notification to NAM the day before.
13	Stedum	53.334000	6.701500	242553	594974	NAM plant, nail, red circle in asphalt. Access 9-17, notification to NAM the day before.
14	Winsum	53.339800	6.540200	231799	595435	In farmers field.
514	Winsum	53.33967	6.54049	231818	595421	Nail, small red circle in asphalt. Notification to owner.
15	Middlestum church	53.347690	6.641020	238498	596425	Church entrance. Narrow and poor light at night.
16	Leermens	53.351800	6.814000	250008	597097	Gras inside NAM plant.
516	Leermens	53.35256	6.814157	250017	597182	Nail, red circle in asphalt. Outside fence of NAM plant.
17	Garsthuizen Garage	53.368090	6.712920	243244	598781	in front of garage gate
18	Bierum	53.372700	6.885700	254733	599520	NAM plant, new asphalt inside.
518	Bierum	53.373148	6.884618	254660	599568	Nail, red circle in asphalt. Outside fence of NAM plant.
19	Uithuizermeeden church	53.408300	6.709600	242941	603252	Church entrance, at top of stairs.
20	Eenrum	53.406400	6.481900	227803	602786	In farmers field.
520	Eenrum	53.40633	6.481649	227786	602778	Nail, red circle in asphalt
21	Usqert	53.425000	6.622300	237104	605007	Gras field inside NAM plant.
521	Usqert	53.424797	6.622533	237120	604985	Nail in asphalt outside fence of NAM plant.
22	Uithuizermeeden	53.449000	6.806200	249275	607904	NAM plant, nail, red circle in asphalt. Access 9-17, notification to NAM the day before.
30	Groningen NS	53.210941	6.565093	233691	581122	Railway station, in corner outside wall of brick house.
33	Assen NS	52.991999	6.570678	234464	556766	Railway station, inside/outside glass wall.
34	Wagenborgen OM	53.254222	6.929877	257956	586398	'Ondergrond Mark'
35	Gasselte OM	52.97151	6.7878	249086	554747	'Ondergrond Mark'
101	Dwarsweg	53.442577	6.731157	244303	607093	Concrete slab of seismic station
104	Uithuizen	53.414688	6.674706	240608	603921	Concrete slab of seismic station
105	Roodeschool	53.418435	6.771330	247024	604457	Concrete slab of seismic station

No	Station name	Latitude (WGS84)	Longitude (WGS84)	RDX	RDY	Description
106	Nieuwstad	53.411102	6.870886	253659	603773	Concrete slab of seismic station
108	Rottum	53.395422	6.643886	238596	601741	Concrete slab of seismic station. Barrier at entrance road, NAM notification the day before.
109	Oldenzijl	53.387850	6.725970	244072	600996	Concrete floor at entrance to a farm
110	Godlinze NAM	53.381600	6.787841	248202	600379	Nail, small red circle in asphalt. Outside fence of NAM plant.
112	Warffum	53.369914	6.571407	233822	598820	Concrete slab of seismic station
113	Huizinge	53.345615	6.675772	240817	596235	Concrete floor at wall of small building. Public site, but owner may be notified. Mr. Elema at +316 222 15 621
114	't Zandt	53.358572	6.770839	247120	597795	Concrete slab of seismic station
115	Krewerd	53.353518	6.862635	253242	597354	Concrete slab of seismic station
117	Westerwijtwerd church	53.334020	6.644610	238764	594908	Church entrance
120	Biessum	53.335292	6.895165	255450	595371	Concrete slab of seismic station
121	Den Haver	53.313374	6.593724	235413	592553	Concrete slab of seismic station
122	Stedumermaar	53.310345	6.677582	241007	592313	Concrete slab of seismic station
123	Garrelsweer	53.309448	6.767519	247003	592324	Concrete slab of seismic station
125	Weiwerd	53.308112	6.943347	258725	592414	Concrete slab of seismic station. Narrow road, best visited during daytime.
127	Ellerhuizen	53.283184	6.628181	237767	589232	Concrete slab of seismic station
128	Woltersum church	53.270720	6.730700	244630	587968	Church entrance
130	Meedhuizen Kerk	53.287670	6.911230	256633	590094	Church entrance
131	Borgsweer	53.296166	7.021767	263982	591201	Concrete slab of seismic station
132	Groningen Beijum	53.249832	6.579190	234561	585466	Concrete slab of seismic station
133	Garmerwolde	53.249902	6.670734	240671	585578	Concrete slab of seismic station
134	De Pauwen	53.252529	6.765041	246959	585987	Concrete slab of seismic station
135	Siddeburen	53.254902	6.862148	253435	586380	Concrete slab of seismic station
137	Woldendorp	53.273928	7.034937	264916	588747	Concrete slab of seismic station
139	Woudbloem	53.225251	6.724081	244282	582900	Concrete slab of seismic station
140	Schildwolde Shell	53.221286	6.807156	249839	582565	Concrete floor. Report at gas station before start.
141	Korengarst	53.223420	6.891871	255491	582917	Concrete slab of seismic station
142	Nieuwolda Kerkelaan	53.221675	6.988644	261958	582863	Concrete slab of seismic station
143	Finsterwolde	53.231821	7.079078	267971	584130	Concrete slab of seismic station. Inform owner before start.
144	Harkstede	53.204167	6.683942	241644	580505	Concrete slab of seismic station
146	Noordbroek NAM	53.191718	6.852396	252927	579335	Nail in asphalt outside fence of NAM plant.
148	Midwolda Strandweg	53.197261	7.028925	264710	580207	Concrete slab of seismic station
149	Hoogezand Foxhol NAM	53.179921	6.725567	244475	577858	Nail, small red circle in asphalt outside fence of NAM plant.
150	Achterdiep	53.179005	6.813773	250374	577869	Nail, small red circle in asphalt at side of road.
151	Zuidbroek NAM	53.173210	6.884778	255134	577321	Concrete slab of seismic station. Barrier at entrance road, NAM notification the day before.
153	Beerta church	53.175030	7.096470	269282	577838	Church entrance.
154	Kiel-Windeweer NAM	53.1232	6.747039	246030	571573	Nail, red circle in asphalt outside fence of NAM plant.
155	Muntendam	53.143327	6.846089	252614	573942	Concrete slab of seismic station
156	Meeden	53.148442	6.930870	258274	574630	Concrete slab of seismic station
157	Winschoten	53.135137	7.022192	264417	573284	Concrete slab of seismic station. Access from busy road, best during daylight.
158	Veendam church	53.105500	6.874800	254622	569773	Church entrance. Near city center, best visited at night or morning.
160	Dallingeweer	53.291290	7.075980	267609	590742	Nail, small red circle in asphalt/concrete aside of road.
161	Zandeweer	53.381850	6.681330	241114	600274	Concrete slab of seismic station
162	Spijk	53.386970	6.841919	251788	601048	Concrete slab of seismic station
164	Oostwold Langeweg	53.220693	7.037981	265255	582828	Concrete slab of seismic station
165	Scheemda NAM	53.171864	6.954295	259785	577270	Nail, small red circle in asphalt outside fence of NAM plant.

No	Station name	Latitude (WGS84)	Longitude (WGS84)	RDX	RDY	Description
166	De Wijert Shell	53.192571	6.566368	233810	579080	At pavement, into the wall of the Shell gas station, at side of gate. Report at gas station before start.
167	Appingedam	53.321365	6.822788	250661	593722	Concrete slab of seismic station
168	Noorddijk	53.237929	6.632431	238138	584201	At entrance of animal clinic, under roof, on brick surface.
169	Engelbert school	53.208725	6.647118	239175	580968	At entrance to school, under roof, on concrete surface.
201	Harkstede	53.223146	6.656331	239762	582584	Nail, red circle in asphalt outside fence of NAM plant.
202	Sappemeer	53.156632	6.804146	249779	575367	Nail, red circle in asphalt outside fence of NAM plant.
203	Eemsweg	53.4317	6.705971	242652	605852	Nail, red circle in asphalt outside fence of NAM plant.
204	Oudeweg	53.24705	6.90257	256150	585562	Nail, red circle in asphalt outside fence of NAM plant.
205	Oude Pekela	53.112056	6.994639	262630	570674	Nail, red circle in asphalt outside fence of NAM plant. Barrier at entrance road, NAM notification the day before.
206	Zuidwending	53.119885	6.950565	259661	571481	Nail, red circle in asphalt outside fence of NAM plant. Barrier at entrance road, NAM notification the day before.
207	Zeerijp	53.346647	6.737620	244933	596426	Nail, red circle in asphalt outside fence of NAM plant. Barrier at entrance road, NAM notification the day before.
208	Eemskanaal	53.240879	6.690317	241996	584598	Nail, red circle in asphalt outside fence of NAM plant.
209	Froombosch	53.187892	6.779603	248070	578813	Nail, red circle in asphalt outside fence of NAM plant.
210	Bedum	53.300011	6.566761	233640	591036	Nail, red circle in asphalt outside fence of NAM plant. Barrier at entrance road, NAM notification the day before.
211	Heiligerlee	53.156214	6.984413	261837	575573	Nail, red circle in asphalt outside fence of NAM plant.
301	Noordpolderzijl	53.461770	6.700400	242221	609191	Nail, red circle in asphalt, at property of Watershap Noorderzijlvest. Access through gate several km's further east. Contact: Mr. Rijploeg 31 610 905 395
302	Oudeschip	53.427380	6.816110	249981	605511	Concrete floor at wall/gate of barn. May call 596 516 219 / 623 757 161
303	Hoogezand Sportshall	53.155400	6.762050	246966	575175	Public area, pavement at flag post outside sporthall.
304	Nieuwolda church	53.243800	6.972900	260852	585301	Church entrance
305	Oostwolderhamrik	53.254280	7.024210	264251	586544	Concrete road, entrance to private house. Call 653 652 484 before each visit.
306	Schaapbulten	53.28135	6.94121	258647	589433	Concrete floor at gate/wall of barn. Call 596 533 248 before each visit.
401	Aurich absolute station	53.468350	7.496840	295089	611182	Basement of hospital. See description in Chapter 5.1.
402	Westerbork absolute station	52.914480	6.605560	236952	548179	Gravity bunker. See description in Chapter 5.2.
403	Kloosterburen infill	53.405760	6.378013	220895	602615	Nail, red circle in asphalt outside NAM plant.
404	Overschild windmill	53.282380	6.784340	248183	589334	Windmill. See description in Chapter 5.4.

Table 3: List of all gravity stations, with number, coordinates and descriptions. Stations which have been replaced with a transfer measurement to an adjacent site are shown in grey.

3 Pre-2015 (4D) stations

A particular challenge in 2015 was to find or identify the locations that were measured in the surveys from 1978 to 1996. Many of these sites were originally inside small huts built above observation wells on NAM properties. All these huts have been removed since the last measurements in 1996, except the one in #6 Haren which was handed over to the local community. Coordinates for stations #2-22 are shown in Table 4, taken from Strang van Hees (1980). Heights are with cm-digit precision. All except 5 of the 42 x,y coordinates end on 0 or 5, indicating the many numbers have been rounded to the nearest 5 m. NAM has supplied text files from the 1996 campaign, having the same x,y coordinates as Stang van Hees (1980), as well as latitude and longitude with four decimals, allowing for an uncertainty of 11 m N-S and 6.6 m E-W. and including stations #30, #33, #34 and #35 as well.

STATION	x (m)	y (m)	H (m)	g (mgal)	$\sigma_{(g-g_0)}$ (mgal)	Δg (mgal)
Gasselte	249.087	564.825	17,84	981.313,890	0,000	−20,28
Annerveen	248.400	567.795	2,05	323,147	0,006	−18,23
Tusschenklappen	254.200	575.280	−0,43	331,581	6	−16,32
Roode Til	258.040	579.565	−0,60	334,178	7	−17,06
Haren	238.980	578.105	0,50	328,854	5	−21,19
Kooipolder	246.910	580.985	−0,28	331,598	5	−20,82
Groningen	234.468	583.077	0,94	332,914	4	−20,94
Tenboer	238.840	586.625	−0,34	335,174	5	−21,79
Schildmeer	253.565	589.435	−0,85	341,816	6	−17,28
Ten Post	245.525	591.170	−0,15	339,186	7	−21,17
Delfzijl	260.640	591.945	0,06	345,498	6	−15,15
Stedum	242.555	594.970	1,18	341,430	6	−21,52
Winsum	231.800	595.435	0,86	341,605	6	−21,95
Middelstum	238.488	596.425	3,07	341,894	7	−21,66
Leermens	250.010	597.095	1,13	345,007	6	−19,51
Garsthuizen	243.250	598.780	2,20	343,916	7	−21,68
Bierum	254.735	599.525	1,21	350,779	7	−15,53
Uithuizermeden (kerk)	242.937	603.250	2,81	348,799	6	−20,10
Eenrum	227.800	602.785	1,64	346,820	7	−22,27
Usquert	237.100	605.005	1,73	353,200	6	−17,48
Uithuizermeden (kabel)	249.275	607.905	1,85	356,439	7	−16,29

Table 4: Station coordinates and gravity from Strang van Hees (1980).

A summary of the pre-2015 stations and their status is given in Table 5. The confidence in positions are qualitatively rated on a scale from 1 (uncertain) to 6 (certain), with estimated lateral and vertical 95% confidence limits as listed in Table 6. The location uncertainties will be discussed individually in the following.

No	Station name	Description	Uncertainty of location [1-5]	Comment
2	Gasselte church	Church entrance	6	Well documented with photo from 1999.
3	Annerveen	Inside building on NAM site	6	Marker is still seen in the floor.
4	Tussenklappen	On grass	2	No evidence of previous site; rely on coordinates. Confirmed with observation well coordinates.
5	Roode Til	On asphalt	2	A patch of new asphalt is found at given coordinates of the old hut.
6	Haren	Inside building on NAM site	6	Marker is still seen in the floor.
7	Kooipolder	On asphalt	2	No evidence of previous site; rely on coordinates. Confirmed with observation well coordinates.
8	Groningen Sint Fraciscuskerk	Church entrance	4	No photo documentation or description. Coordinates deviate about 15 m from entrance, and are proven wrong because height fit with the top of the stairs, not the pavement which the coordinates points to. Measuring at church entrance seems to have been common past practice.
9	Ten Boer	On asphalt	2	Position of old hut is seen because asphalt is newer. Agrees with given coordinates.
10	Schildmeer	On grass	2	No evidence of previous site; rely on coordinates. Confirmed with observation well coordinates.
11	Ten Post	On grass	1	Previous site was the floor of a heating room in main-control building. No evidence of previous site; rely on coordinates.
12	Delfzijl	On grass	2	No evidence of previous site; rely on coordinates. Confirmed with observation well coordinates.
13	Stedum	On asphalt	2	Position of old hut is seen because asphalt is newer. Measured 2-3 m aside of the new asphalt.
14	Winsum	On grass	2	No evidence of previous site; rely on coordinates. Confirmed with observation well coordinates.
15	Middelstum church	Church entrance	4	No documentation. Given coordinates points to a grave about 8 m from entrance, and are proven wrong because the height fits with the church entrance, where the 2015 measurements were recorded.
16	Leermens	On grass	1	Previous site was the floor of a heating room in the main-control building. No evidence of previous site; rely on coordinates.
17	Garsthuizen	On concrete	4	Likely position in front of garage door, a few meters aside of the given coordinates. Agrees with height.
18	Bierum	On asphalt	2	Position of old hut is probably seen because asphalt is newer. Agrees with given coordinates.
19	Uithuizermeeden church	Church entrance	4	Close to given coordinates, but not confirmed with new height measurements.
20	Eenrum	On grass	2	No evidence of previous site; rely on coordinates. Confirmed with observation well coordinates.
21	Usquert	On grass	2	No evidence of previous site; rely on coordinates. Confirmed with observation well coordinates.
22	Uithuizermeden	On asphalt	2	Position of old hut is seen because asphalt is newer. Agrees with given coordinates.
30	Groningen NS	At railway station	5	Documented with photo. Height difference due to new pavement cover after 1996 is estimated from photos; about 6 cm higher in 2015.
32	Winschoten NS	At railway station	Given up	Documented with photo. Major rebuilding inside since then. Decision to give up the location in 2015.
33	Assen NS	At railway station	6	Documented with photo from 1999. Unchanged since then.
34	Wagenborgen OM	Well defined	3	Measured inside hole in 1996, on top in 2015. Exact vertical position of gravimeter in 1996 is not known.
35	Gasselte OM	Well defined	3	Measured inside hole in 1996, on top in 2015. Exact vertical position of gravimeter in 1996 is not known.

Table 5: Status in 2015 of the 26 stations that were measured in 1996 and earlier.

Uncertainty category	Description	Lateral 95% confidence [m]	Vertical 95% confidence [cm]
1	Only coordinates from gravity files	<100	<2
2	Coordinates from gravity files and observation well	<5	<2
3	OM	<1	10
4	Church entrance with some deviation from given coordinate	<3	<2
5	Picture, but some vertical uncertainty	<1	<3
6	Picture, same surface in 2015 as before	<1	<1

Table 6: Position uncertainty categories for various old sites.

Stations 2, 3, 6, 8, 15, 17 19, 30, 33, 34 and 35 can be recognized with some confidence from either description or photo (see description of each site below). The coordinate agreements between 1978-96 and those measured in 2015 (with cm precision laterally) are listed in Table 7. For these stations, this comparison serves as quality control on the coordinate accuracy in 1996 and earlier, since the locations are known to be the same. The distribution of errors is far from random. Station 35 Gasselte OM can clearly be regarded as an outlier, because an error of 10 000 m probably arises from a typing error in one digit. Stations 3 Annerveen, 30 Groningen NS and 33 Assen NS are 132 m, 91 m and 34 m off, respectively, as documented by old photographs for the NS stations and painting on the floor for Annerveen. These discrepancies are far more than any reasonable positioning uncertainty, and may also be classified as outliers, for some unknown reasons. For the remaining stations, the standard deviation of distance error is down to 5 m, with the 18 m at Groningen Sint Fraciscuskerk as the largest deviation. In summary, 6 or 7 of the 10 stations have accurate coordinates from the 1990's, but 3 or 4 stations have not.

No	Station name	Deviation [m]	Comment
2	Gasselte church	7.3	
3	Annerveen	132.1	Unexplainable large deviation
6	Haren	3.2	
8	Groningen Sint Fraciscuskerk	17.9	
15	Middlestum church	10.0	
17	Garsthuizen Garage	6.1	
19	Uithuizermeeden church	4.5	
30	Groningen NS	91	Large deviation, these coordinates are not from Strang van Hees (1980) and may be from a less accurate source
33	Assen NS	34	Large deviation, these coordinates are not from Strang van Hees (1980) and may be from a less accurate source
34	Wagenborgen OM	3	
35	Gasselte OM	(10000)	Likely mistype of 10 km digit in x-y format

Table 7: Deviation in lateral position between (i) coordinates given in either Strange van Hees (1980) or the data files from 1996, and (ii) measurements at the same locations in 2015.

Stations 5, 9, 13, 18 and 22, all inside NAM plants, have a rectangular area of newer asphalt likely to be the true location of the old observation hut. Of these, only station 13 coordinates are slightly (about 2 m) outside the patch of new asphalt. Stations 7 and 12 do not show a small patch of newer asphalt, but NAM has confirmed them to be at the place of the old huts.

Stations 11 and 16 were inside control rooms in past surveys, and measured on grass in 2015. We have seen no independent evidence of the correctness of their 2015 position, and these are therefore put in uncertainty category 1.

Stations 2, 30, 33, 34 and 35 all belong to the NedZwa network, the first order gravity network of the Netherlands (De Min 1995). After comparison of values, Bilker (1996) decided not to use the NedZwa93 values at all, and we have done similarly.

3.1 Station 2 Gasselte church

Measurement position at the entrance is seen on picture from 1999 (Figure 2, left side).

Figure 2: Photos of the Gasselte church gravity measurements September 23rd 1999 (left, using LCRG785 and LCRG487). Photo obtained from Marc Crombaghs. Right: measurement done September 18th 2015. Photo from Quad's night crew.

3.2 Station 3 Annerveen

This site still has a painted marker in the floor from the 20th century surveys, and the position uncertainty is thus insignificant. It is inside a control building on a NAM facility, and no rebuilding has been reported since the 1990s.

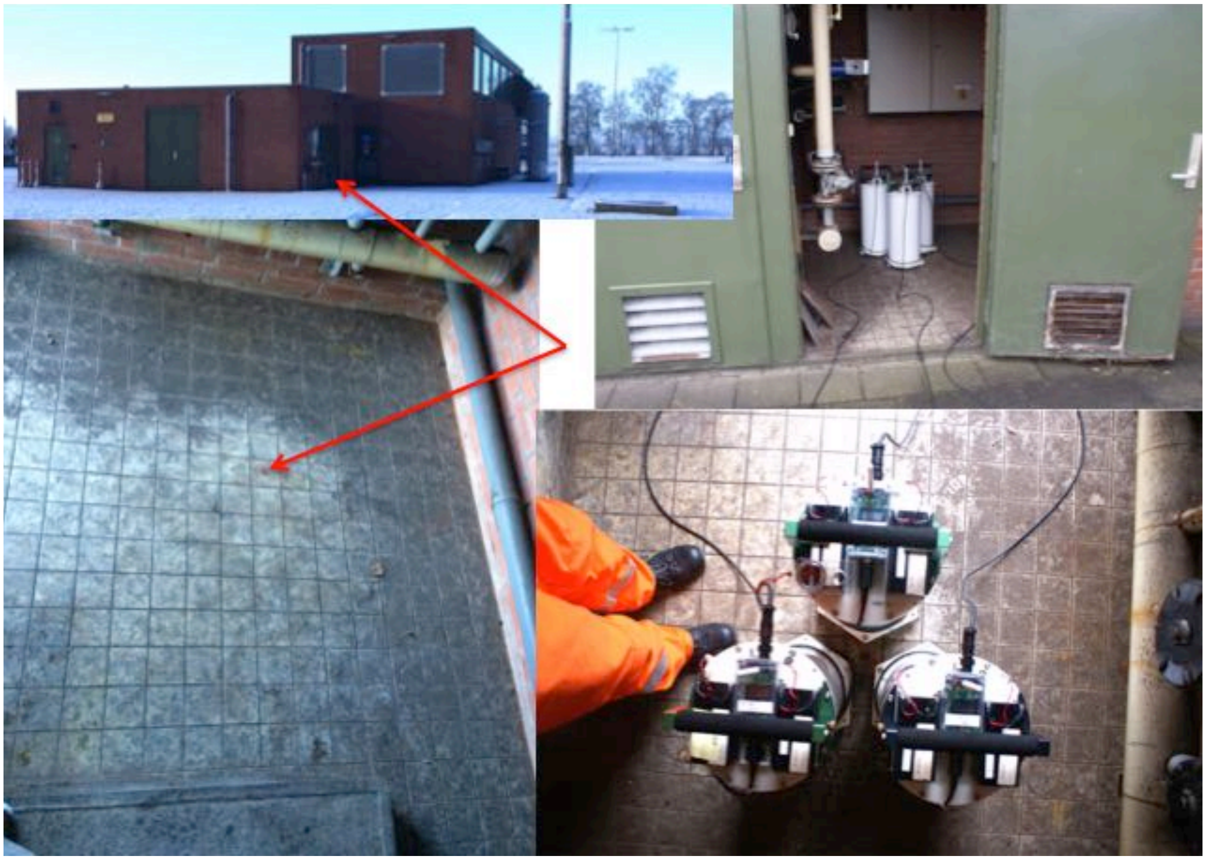

Figure 3: Photos of the Annerveen gravity site, with a marker in the floor from the last century's measurements.

3.3 Station 4 and 504 Tussenklappen

The observation hut has been removed and the area has been brought back to grass land. A NAM surveyor was confident that the given coordinates are where the hut was. The site was transferred to the nearby asphalt 22 m away in 2015, using a portable benchmark in the grass (Figure 4).

Figure 4: Photos from station 4 (on grass, marked with wooden pins on the upper left picture, and 504 marked with a red painted circle.

3.4 Station 5 Roode Til

A footprint of the observation hut can be seen as a square of darker asphalt (Figure 5). This site was not transferred in 2015. The ground is estimated to be 21 cm lower in 2015 than earlier (Table 37).

Figure 5: Photos from station 5 Roode Til.

3.5 Station 6 and 506 Haren

The old site was inside the only observation hut remaining. The painting from the gravity point was still seen on the floor (Figure 6). The new station is marked with a pin in the asphalt outside the fenced area with the hut, which now belongs to the local community.

Figure 6: Photos from station 6 (lower right), 506 (upper part) and from Google Map (lower left).

3.6 Station 7 and 507 Kooipolder

The old station is inside the fence where new asphalt can be seen. The new station was established on the asphalt on the outside, 9 m away.


Figure 7: Photos from station 7 (upper right) and 507.

3.7 Station 8 Groningen Sint Fransiscuskerk

The coordinates from Table 4 are on the pavement between the church entrance and the house next to it, 18 m from the church entrance. We believe it was common practice to measure at the entrance to churches, as was done in the Gasselte church (Figure 2), and selected the site accordingly. The entrance is two steps up from the pavement, and comparison of height measurements give independent information on the past location. The height of the selected point at the entrance (Figure 8) agrees with the 1996 height and estimated subsidence since then within 5 mm (Table 38).

Figure 8: Photos from station 8.

3.8 Station 9 Ten Boer

The position of the hut can be clearly seen in the darker asphalt (Figure 9). The surface level is estimated to be lowered by 8.5 cm in 2015 compared to earlier, after subsidence is taken into account (see Table 37 and later discussion).

Figure 9: Photo from station 9.

3.9 Station 10 and 510 Schildmeer

The original coordinates were in 2015 on grass (Figure 10). A new station was defined at the end of the asphalt road outside the fence.

Figure 10: Photo from station 10 (right) and 510 (left).

3.10 Station 11 and 511 Ten Post

The original location was inside a control room, in a building which was removed between 1996 and 2015. We have no independent evidence of the correctness of the position, which now is on grass, close to the gas treatment facility (Figure 11). The new station is on the asphalt outside the main gate.

Figure 11: Photo from station 511 (left) and 11 (right).

3.11 Station 12 and 512 Delfzijl

The coordinates of the old station is a location which now is on grass (Figure 12). No physical evidence of a hut was found. The new location is only 4.5 m away.

Figure 12: Photo from station 12 and 512.

3.12 Station 13 Stedum

The coordinates are just outside the square of newer asphalt (Figure 13). The position should probably have been moved a few meters to be inside the square. Height change from 1996, after correction for subsidence, is only 2.8 cm.


Figure 13: Photo from station 13.

3.13 Station 14 and 514 Winsum

The coordinates of the old station is now in a farmers field, as can be seen from the portable benchmark in Figure 14. Height is 45 cm lower, causing a large gravity height correction, with uncertainty in which density to apply for the removed mass. The new point is defined on the side of the entrance road to the farm.


Figure 14: Photos from station 14 (left) and 514 (middle and right).

3.14 Station 15 Middlestum church

The coordinates in Table 4 are at a grave 10 m left of the entrance. The past location is more likely to be right at the entrance, like for the Gasselte and Uithuizermeeden churches, and this was selected for measurements (Figure 15). The height of the entrance corresponds with the 1996 heights and subsequent subsidence within 5 mm (Table 38), and strongly supports the choice of the church entrance as location.

Figure 15: Photo of station 15.

3.15 Station 16 and 516 Leermens

The location was inside a control room in past surveys. The coordinates is now on grass (Figure 16), and no hints of the control room building can be seen. The new location is on asphalt outside the main gate.

Figure 16: Photo of station 516 (left) and 16 (right).

3.16 Station 17 Garsthuizen

The location was in Bilker (1996) described as "Garsthuizen Garage". The location was moved 6 m from the nominal coordinates, to the position just at the gate (Figure 17). The height agrees with the 1996 height and later subsidence within 1.6 cm (Table 38).

Figure 17: Photos of station 17.

3.17 Station 18 and 518 Bierum

The old station is on a patch of asphalt that may indicate removal of an observation hut (Figure 18). A height reduction (Table 34) of 14 cm has been measured. The new location is moved outside one of the side gates of the facility.

Figure 18: Photos of station 518 (left) and 18 (right).

3.18 Station 19 Uithuizermeeden church

The church has been measured in all campaigns. Bilker (1996) wrote: "*Investigation pointed out that new stairs were made in front of the church, so the measurements in 1996 were made 20 cm higher than in 1988.*" The gravity values in 1996 were in Bilker (1996) reduced with a free-air correction to the level of 1988.

Figure 19: Photos of station 19.

3.19 Station 20 and 520 Eenrum

The old station is now in a farming field (Figure 20, right). Height is 14 cm lower than estimated from 1996 and later subsidence (Table 34). The new station is at the end of a small asphalt road.

Figure 20: Photos of station 520 (left) and 20 (right).

3.20 Station 21 and 521 Usquert

Coordinates of the old station is on grass (Figure 21). No physical evidence of an observation hut can be seen. The new station is on asphalt outside the fence.

Figure 21: Photos of station 21 (left) and 521 (right).

3.21 Station 22 Uithuizermeeden

The observation hut can be seen as a square in the asphalt (Figure 22), and the 2015 measurements were made in the middle of it. Several large tanks are located near the site (Figure 22 and Figure 23). These were built after the 1996-survey.

Figure 22: Photo of station 22.

Figure 23: Map view of 11 diesel storage tanks that have recently (after 1996) been built near station 22 (seen as dark green square near the western corner of the light green NAM site. Source: Marcin Glegola, Shell.

Each tank has a size of 60000 m^3. The owner (Vopak) confirmed that the storage tanks are full at all times, for strategic reasons. Marcin Glegola in Shell has calculated the gravity attraction from the content of the tanks. The mass of the tank itself has not been taken into account. Tank volume and content are based on information from a board in front of the tank. Diesel is stored, with assumed density 835 kg/m^3. A cylinder with radius 30 m and height 21 m has been modeled. Distance from nearest tank to gravity station is about 75 meters (Figure 23). If all tanks are full, a gravity signal of 6-7 µGal is modeled (Figure 24). The 2015 gravity value at station 22 has been increased by 6.5 µGal before time-lapse analysis.

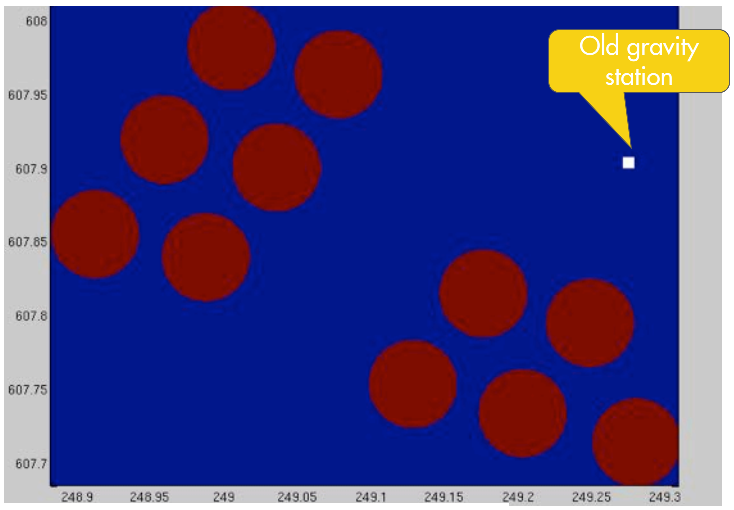

Figure 24: Map view of tank model, from Marcin Glegola, Shell.

3.22 Station 30 Groningen NS

This point was first measured in 1984. It is one of the points of the first order gravity network of the TU Delft (Delft University of Technology). A photo exists from a gravity measurement made in 1999 (Figure 25, right side). The 2015 measurements were made in the same corner, with the unaltered building wall behind. However, the floor has been changed between 1996 and 2015, and raised a few cm, as can be judged from the height of the lowermost gray part of the wall behind. The height measurements (Table 37), show almost no change between 1996 and 2015 and an expected subsidence of 3.9 cm. This corresponds to an increased elevation with respect to the wall of about 3.8 cm.


Figure 25: Photo of station 30, in 2015 (left) and 1999 (right).

3.23 Station 33 Assen NS

A picture from a gravity measurement at the railway station in Assen in 1999 is available (Figure 26, left). The floor and wall of the site were unaltered in 2015. The 2015 measurement were made on the outside of the glass wall (Figure 26, right). There is no height difference between the inside and outside.

Figure 26: Photo of station 33, in 1999 (left) and 2015 (right).

3.24 Station 34 Wagenborgen OM

OM is short for Ondergrond Mark, and this is a hole with an iron cover (Figure 27), easily identified. The gravity measurements in 1996 were done inside the hole, while the instruments in 2015 could not fit into the hole and were made on top of the iron cover (Figure 27).

Figure 27: Photo of station 34.

3.25 Station 35 Gasselte OM

This is, similar to station 34, a hole with an iron cover (Figure 28). The 2015 measurements were made on top of the iron cover, while the 1996 measurements were made inside the hole.

Figure 28: Photos of station 35.

4 New infill stations

73 new stations were defined in 2015. Thirty-four of the newly established seismic stations with concrete platforms were used as benchmarks for gravity readings, and 33 new stations were marked with a nail in the asphalt, in public areas outside the fence of NAM sites or at other public or private sites. Six new stations were at church entrances.

4.1 Geophone stations

The geophone stations were installed in 2015 on top of a borehole with seismic sensors installed, containing an electronics and transmitter box on a concrete plate (Figure 29). The plate is 140 mm thick, with a free rectangular space of about 1000 mm × 375 mm on each short side. Three gravimeter units fit easily on this surface (Figure 30). The chosen side of the platform was to the right when facing the front doors, except for stations 112, 139, 141 and 142, which were on the left side. The tilts were measured on many of the stations prior to the 2015 survey, and were mostly <0.2°.

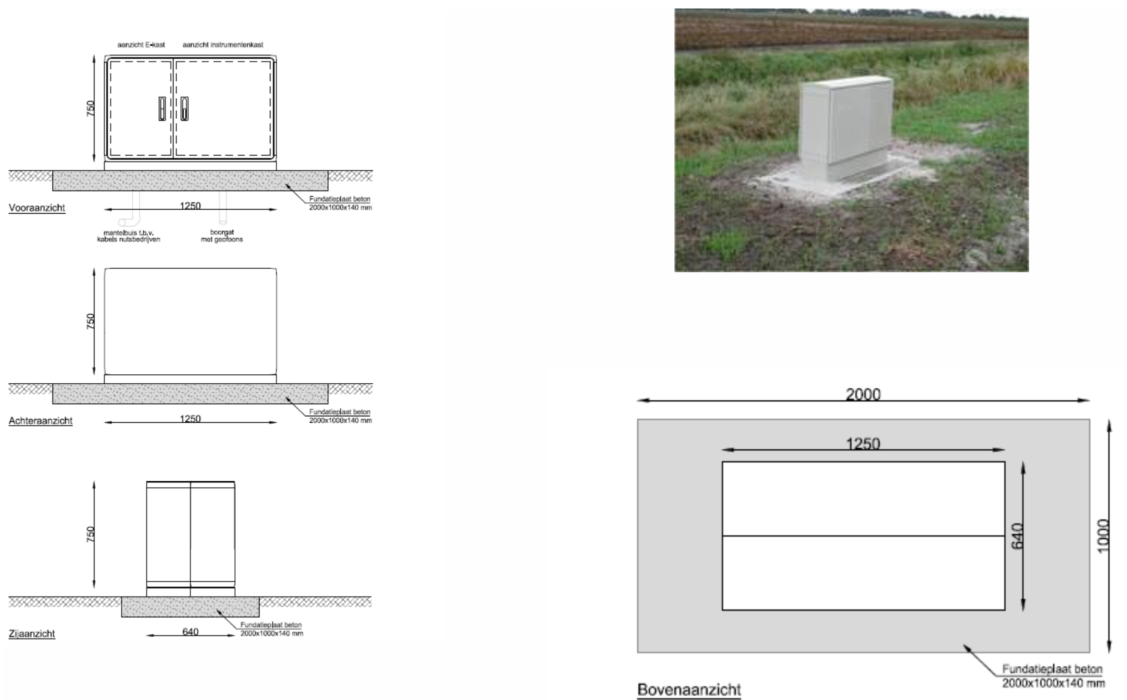

Figure 29: Dimensions of the seismic observation platforms.

Figure 30: Sketch of how the three gravimeters are placed onto the short side of the concrete platform.

Figure 31: Picture of gravimeters on a seismic station (#123).

4.2 Stations on asphalt

The stations on asphalt were marked with a nail in 2015 (Figure 32). For most of the nails, a red circle was painted around (Figure 33). The painting is likely to disappear before the next round of measurements. For station 521 it disappeared within a few weeks. Nail positions have been recorded with a few cm's precision (Table 3), and can thus be re-established if needed.


Figure 32: Nail in asphalt, without red painting around (station 521).


Figure 33: Nail in asphalt with painted red circle around (station 520).

5 Reference stations

Three reference stations were established outside the area of influence from the gas production, in different directions; 401 Aurich, 402 Westerbork and 403 Kloosterburen (Figure 1). These were included in the main survey with three measurements on each. Two of the sites (Aurich and Westerbork) have previously been measured with absolute gravity.

5.1 401 Aurich

This site is in the basement of the “Kinderklinik, Kreiskrankenhaus” (children clinic in the hospital), Wallinghausener Strasse 12, Aurich, Germany (Figure 34). The contact person in 2015 was the technical leader Harald Adam (0049 4941 941919, E-mail: herald.adam@u-e-k.de). The site had to be visited during office hours.

Bundesamt für Kartographie und Geodäsie (BKG, www.bkg.bund.de) is responsible for the 30 stations main gravity network of Germany (Schweregrundnetz, DSGN94), of which 401 Aurich (DSGN94_3/1) is a part. Contact person is Dr. Reinhard Falk (reinhard.falk@bkg.bund.de).

The main and alternative absolute sites in the area have been measured 3 times with FG-5 during the last 15/20 years. A seasonal change of some μGal could be expected, but Reinhard Falk reported in 2015 (by E-mail) that “they could not find significant (time-lapse) gravity changes in the area”. The gravity value and vertical gradient can be found in http://agrav.bkg.bund.de/dsgn94/DSGN94.pdf and are listed in Table 32.

Figure 34: Pictures from the reference station 401 Aurich. A golden plate in the floor marks the site.

5.2 402 Westerbork

The bunker is situated on a property controlled by Radiosterrenwacht Westerbork and Astron (www.astron.nl, bewaker@astron.nl). Quad's gravity crew borrowed a key to the bunker from the Radiosterrenwacht for the whole survey period, after recommendation from Rene Reudink at TU Delft. The Radiosterrenwacht on-site staff can be contacted by email secretaryobservatory@astron.nl or phone 0521 595 728 / 776 / 790. The Westerbork Synthesis Radio Telescope (WSRT) area is a restricted access zone for vehicles. Within this zone, use of mobile phones (GSM) or wireless recorders is prohibited, and these devices must be switched off or set to "airplane" mode when approaching the site. On the approach, turn right after driving past an old wooden house inside glass, then turn left before the one-stock administration building. Paved roads brings you 20 m from the entrance, and it is under dry conditions possible to drive on grass to the entrance. The site is in the middle of the concrete platform, marked with 3 black circles (Figure 35).

The Westerbork "gravity bunker" has been measured yearly by TU Delft, last time 10th-11th of June 2015. The absolute gravity values were received from Rene Reudink at TU Delft in an e-mail September 21st 2015. The absolute gravity at floor level is 981 309 070.1 +/- 1.0 µGal and at 1.3 m 981 308 689.7 +/-0.6 µGal. The vertical gradient is -2.926 +/- 0.006 µGal/cm.

Figure 35: Pictures from the gravity bunker in Westerbork.

5.3 403 Kloosterburen

This site is northwest of the Groningen field (Figure 1), outside a NAM plant (Figure 36), and was measured for the first time in 2015. No absolute measurements existhere.

Figure 36: The reference site in Kloosterburen.

5.4 404 Overschild

The windmill *Windlust*, built in 1859 (Figure 37), served as the central reference station for the loops, and also as an absolute gravity tie. The measuring point is near the center of the mill, on the concrete ground floor (Figure 37, right side), of unknown age and underlying constitution. A nail was put into the floor after the 2015 survey to mark the exact location of the gravity point. The absolute measurements, also done in September 2015, are described on page 86.

Figure 37: Windmill "Windlust" in Overschild (left), with gravimeters inside (right).

6 Data acquisition

6.1 Equipment

The 1978-1996 surveys used LaCoste & Romberg (LCR) gravimeters with various serial numbers, shown in Table 8. The instrumentation for these surveys was briefly summarized in Bilker (1996). G. L. Strang van Hees from the TU Delft carried out the first measurements in 1978. A LCR gravimeter was borrowed from the Technical University of Hannover (van Hees 1980). Strang van Hees was also responsible for the 1984 measurements, using a LCR gravimeter borrowed from the Technical University of Darmstadt. The 1988 measurements were made by P. Plugers from the TU Delft. The 1996 measurements were carried out by P. Plugers and M. Bilker from the TU Delft. The 1996 measurements were made with two instruments and one survey car, and with sequential readings of the two instruments at each site. Bilker (1996) states that "*The G785 was sensitive for disturbances and showed sometimes an instable behavior. The measurements were made faster than expected, although some bad weather conditions were experienced*".

Not much data acquisition details from these surveys can be found in the published papers. The measurements had a progression of about 1 hour per station, and it was surveyed during 8 to 10 hours each day.

Year	Gravimeter type	Serial number
1978	LaCoste & Romberg	G079
1984	LaCoste & Romberg	G258
1988	LaCoste & Romberg	G785
1996	LaCoste & Romberg	G785 & G971
2015	Scintrex CG5	U10, U11, U12, U13

Table 8: The serial number of LaCoste & Romberg gravimeters used in 1978-1996 and unit numbers used in 2015.

The 2015-survey can be described in much more detail. The following equipment was used:

- Four CG5 sensors with gimbals mounted inside lightweight aluminum cylinders, shown in Figure 38. Weight was about 15 kg for each complete unit Three units were used at a time in the survey and the fourth served as spare. The height of the gravity sensor core (spring) was 25 cm above ground.
- Power supply was mainly from car batteries; during transport and at stations within reach of about 12 m long cables from the car. Two sets of 2 × 120 Ah car batteries were used, with batteries replaced and recharged once a day. For stations out of reach for the cables, power was supplied from a light battery package mounted on top of each unit.
- Wireless or wire communication (instrument control and data transmission) between the units and a recording computer, dependent upon cable reach.
- A 122 cm wide 4-unit transport rack, mounted in the broadside back of the survey car.
- Two portable benchmarks, each of weight 25.8 kg (Figure 39). They consist of an aluminum plate with 3 leveling feet and a hole in the middle, "cups" to place gravimeters in, and bubble level(s) attached
- Air pressure sensors.
- Acquisition and processing computers.
- Reference gravimeters for measuring earth tides: One Micro-g LaCoste Model gPhoneX and one LCR instrument.

- Absolute gravimeter; FG-5 from the Technical University of Delft.
- Data acquisition software for controlling the leveling of sensors, the recording and QC of parameters, in LabView language.
- Data processing software; QuadPro

Figure 38: Left: Inside of gravimeter housing with gimbal frames and CG5 sensor cores. Middle: All four gravimeters fitted into the frame in the back of the survey car. Right: Three gravimeters on a seismic station (right).

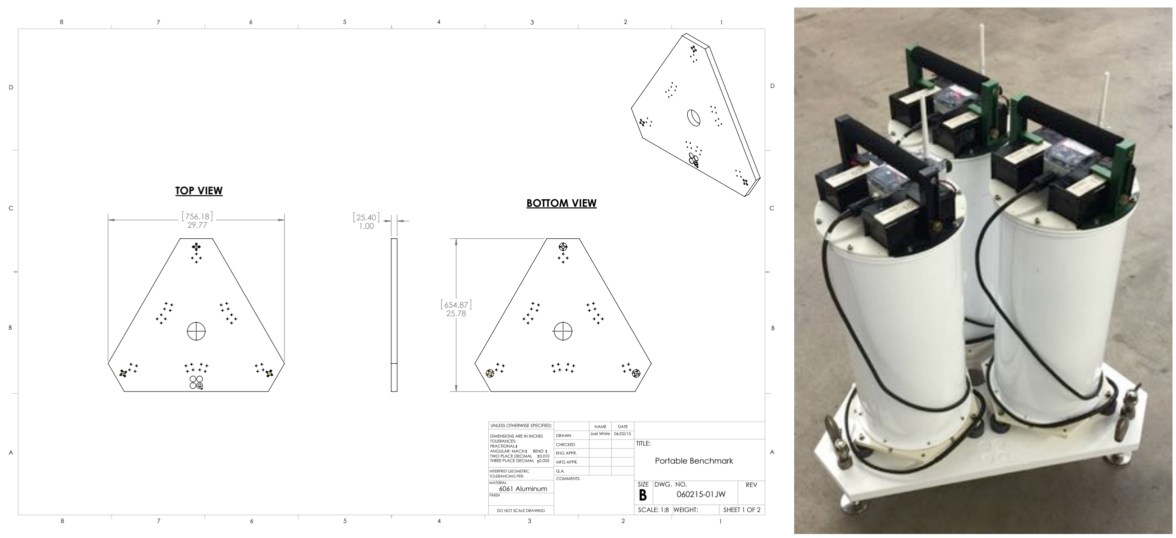

Figure 39: Portable benchmark, drawing (left) and picture with gravimeters mounted on top (right).

A Mercedes Vito (Figure 40) with thermo-insulation and separate temperature control in the back room was the main car used for surveying. Navigation systems and laptop computers got power from the 12V outlet.

Figure 40: The survey car: A Mercedes Vito from KAV Autoverhuur.

A WV Caddy with two seats and air conditioning in the front was used for crew-changes and some material supplies. It also served as a backup car for the survey, and was used one day for the transfer measurements. An Opel Zafira with 7 seats / cargo space was used for person transport, and for transporting equipment from Trondheim to Groningen and back.

Two independent navigation systems were used in the survey car: A TomTom GO 6000 and an Ipad with sim-card set up for interactive use of Google maps. The app MyTracks recorded the route, and tracking of the car's position could be done by any crew member with the App *Life360*. Navigation in the crew-change car was done by a second TomTom GO 6000 or by personal smartphones.

The crew took pictures of the instrument setup at each site, with a hand-carried camera. The photos are stored as raw survey data, categorized by station numbers.

Figure 41: Gravity recording in 2015, during the Bierum transfer measurement.

The following improvements of the equipment were identified in the post-survey summary meeting on September 27th:

- Skids to put under the wheels to be available in the back of the car, in case the car got stuck in soft soil or mud.
- Cruise control could be convenient when driving on the motorway. Not much time was spent on the motorway, though.
- A survey car with 4-wheel drive would make the driving off the road more robust. On the other hand, NAM has experience with contractors driving 4-wheel cars in the field without asking permission from the land owner first. The sense of safety felt by having a big and powerful vehicle may cause the driver to forget the footprint it can leave behind.
- The cooling system in the back of the car was regulated by a thermostat with a few ^{o}C of tolerance before it triggered. This caused the cooler to nearly never turn on. This shows that the thermal insulation worked well and avoided heating from sun radiation in the middle of the day. Thermal insulation may be sufficient thermal control.

6.2 Logistics, personnel, timeline and communication in 2015

Each crew of two people (driver/assistant and data acquisition technician) worked 8-hour shifts, with crew changes at 01:00, 09:00 and 17:00 local times. The same schedule with the same people was kept for the whole survey. Daylight hours are shown in Table 9. There were about 2-3 hours of daylight for the evening and morning crews.

Date	Civil twilight	Sunrise	Sunset	Civil twilight
September 14th	06:30	07:05	19:53	20:28
September 21st	06:42	07:17	19:36	20:10
September 28th	06:55	07:29	19:19	19:53

Table 9: Sunrise and sunset for Groningen September 2015.

The crew changes took place at the station closest to the recording car at the nominal time of change. All stations except the three outside references, which were avoided for crew changes, are within 35 minutes' drive from Ten Boer. Including driving time and 5-10 minutes briefing for the ongoing crew, a shift lasted about 9 ½ hours.

The outgoing crew was briefed about the plan for the shift in the operations center before driving to the place of the crew change. Quad's project leader issued a work description with the sequence of stations to measure and particular safety concern or other issues to pay attention to. Toolbox talks took place at all crew changes. The following issues were covered during the handover:

1. HSE incidents and near misses.
2. Operational experiences, with potential improvements and watch-outs.
3. Results from measurements, with technical issues and concerns.
4. Last minutes risk assessment for the activities of the upcoming shift

The base of operations was the village of Ten Boer (Figure 42), where the crew stayed at Hotel de Pleisterplaats. The living room in a 3-bedroom apartment served as Quad's operations center during the survey. A garage next to the hotel (Figure 42 and Figure 43) served as a workshop.

Figure 42: Map photo of hotel and workshop area in Ten Boer.

Figure 43: Garage in Ten Boer, where the workshop during the gravity operations was established.

The personnel, their position and dates of arrival and departure are listed in Table 10.

Name	Function	Arriving from	Arrival date	Departure date
Ola Eiken	Project leader	Trondheim	September 3rd	September 29th
Joel White	Technician	San Diego	September 3rd	October 2nd
Mark Zumberge	Technical advisor	San Diego	September 5th	September 14th
Michael Davis	Technician	San Diego	September 8th	October 2nd
Tom Eirik Slettahjell	Programmer/driver	Trondheim	September 8th	September 28th
Billy Hatfield	Technician	San Diego	September 9th	September 28th
Dave Jabson	Technical advisor	San Diego	September 9th	September 16th
Snorre Sulheim	Physicist/driver	Trondheim	September 9th	September 28th
Patrick Paitz	Driver/geophysicist	Stuttgart	September 9th	September 28th
Rob Paesens	Driver (Taxiroden)	Local	N/A	N/A
Siebe van der Pruik	Driver (Taxiroden)	Local	N/A	N/A
Renè Reudink	Technician (TU Delft)	Delft	September 16th	September 17th

Table 10: Quad personnel for the survey, with functions and dates of arrival and departure.

Quad's organizational chart for the Groningen 2015 project is shown in Figure 44.

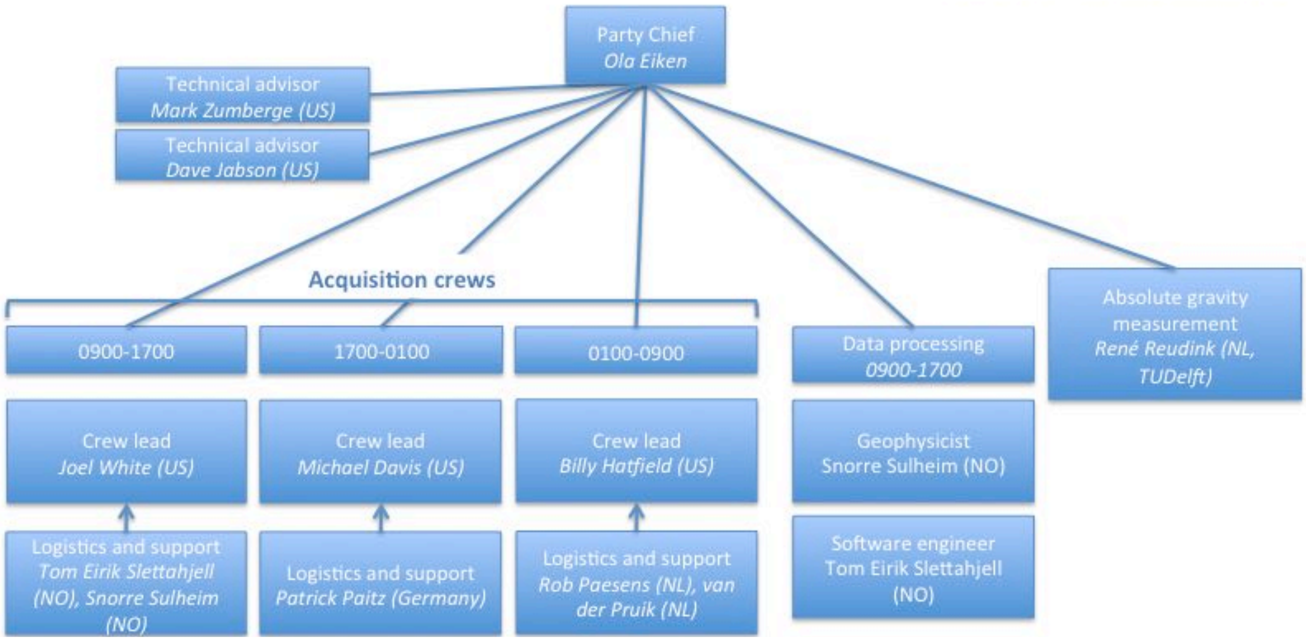

Figure 44: Quad roles and responsibilities for the Groningen 2015 gravity survey.

Most of the personnel travelled to the Netherlands by air, from San Diego and Trondheim, respectively. Ola Eiken drove a car with various survey equipment, computer screens, printer, etc. from Trondheim to Ten Boer. The recording equipment was sent by airfreight from San Diego on the 25th of August. René Reudink packed the equipment for the absolute gravity measurement in a transport car the morning of September 16th, before driving the 255 km from Delft to Overschild.

A timeline of the operations in the Groningen area is shown in Table 11.

Date	**Action**	**Personnel US**	**Personnel NO**
September 3rd	Arrival, unpack instrument, put the gravity sensors on heat	Joel W	Ola E
September 4th	Safety training at NAM Kick-off meeting between Quad and NAM, with review of acquisition plan Mobilize instrument	Joel W	Ola E
September 5th	Mobilize car for measurements	Mark Z Joel W	
September 6th	Scale factor calibration	Mark Z Joel W	Ola E
September 7th	Transfer of values to new 4D sites. Two NAM production sites to be done between 9 and 17, a public or private site thereafter. Prepare stations/route	Mark Z Joel W	Ola E
September 8th	Transfer of values to new 4D sites. Two NAM production sites to be done between 9 and 17, a public or private site thereafter. Safety briefing for the absolute measurement at NAM, Assen Prepare stations/route Arrival of crew members	Mark Z Joel W	Ola E

September 9th	Transfer of values to one public new 4D site, after 4 pm. Complete absolute measurement in Overshild Safe driving training Arrival of remaining crew	Mark Z Joel W	Ola E Tom Eirik S
September 10th	Individual safety lessons at NAM Safe driving training Crew meeting for all personnel, 18-20 hours. Transfer of values to one public new 4D site, after 4 pm.	All	All
September 11th	Project safety meeting, for all participants 9-12 hours in NAM's office. Transfer of values to two non-production NAM sites in the afternoon.	All	All
September 12th	Transfer of values		
September 13th	Survey starts in the morning 0900	Joel W Michael D Billy H Mark Z Dave J	Tom Eirik S Snorre S Ola E Patrick P Rob P (Taxiroden) Siebe vdP (Taxiroden)
September 16th	Start of absolute measurement in Overschild		René R (TU Delft)
September 17th	End of absolute measurement in Overschild		René R (TU Delft)
September 27th	Survey completion Transfer of values at #14 Post-survey summary meeting with all crew Crew dinner		
September 28th	Departure of most of the crew Transfer values De-briefing at NAM office		Ola E
September 29th– 30th	Scale factor calibration survey to Zwolle and Maastricht	Joel W Micahel D	
October 1st	Packing of equipment	Joel W Michael D	
October 2nd	Pick up of equipment	Joel W Michael D	

Table 11: Timeline of operations in the Groningen area.

Quad Geometrics had dedicated mobile phones in the operations center (Quad's emergency phone with 24 hours duty), in the recording car, and in the garage / with the technical support. The party chief (Ola Eiken) was also available on his cell phone, and he was the point of contact for NAM/Shell.

NAM emergency contacts were Wim van der Veen (survey department leader at NAM, Assen) and Shizhuo Liu (company representative and surveyor at NAM, Assen). Shell geophysical support was Marcin Glegola. The crew called the central control room (CMK) before work commenced, and after work finished, on or outside the fence of NAM sites. A chart of the NAM/Quad interface is shown in Figure 45.

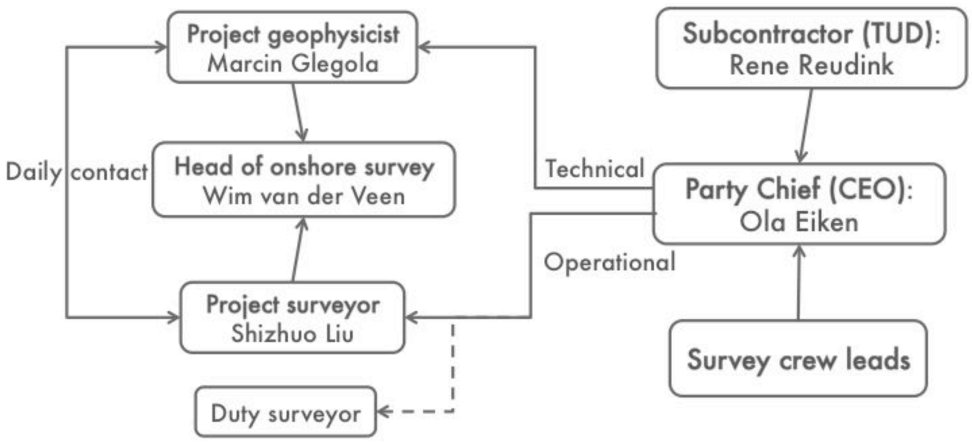

Figure 45: Chart of the NAM and Quad interface during the 2015 survey.

The daily reports from Quad to NAM are shown in Appendix C, page 169.

6.3 Site accessibility

NAM provided permits and access grants. Several sites were defined or got access during the first week of the survey, and the first visit on those stations were delayed a few days. All stations had at least two days between each visit.

NAM production sites (#3, 5, 9, 512, 13, and 22) were accessed between 9-17 hours on weekdays, with a NAM surveyor accompanying the Quad team. This was arranged with a notification from Quad to NAM the day before. A NAM pass was issued for all crewmembers. Although the NAM surveyor took care of the required work permit, all shift leaders took a 4 hour NAM course making them able to acquire a work permit. The survey vehicle drove to the measurement sites inside the plant.

Six stations (#108, 151, 205, 206, 207 and 210) had a barrier across the access roads. On Quad's notification the day before, these were opened by a NAM surveyor in the morning and closed again at the end of the office working hours. Hence, they had to be visited during office hours.

For all sites at or close to a NAM plant, NAM's control center was called upon arrival, and again when the measurement was completed.

The railway stations in Groningen and Assen are busy and noisy during daytime, and were always visited during nighttime.

The Aurich absolute station in the basement of the hospital had to be visited during office hours (8-16).

The private site #306 was inside a gate, accessible 7-20. The seismic stations #125 and #157 had difficult parking conditions, and were only visited during daytime. For nine of the stations, the site owner had asked for a notification prior to the visits. There were no problems with the access, and the notification was not always necessary on the second and third visits.

Remaining locations were accessible 24/7 for Quad personnel, without accompanying persons needed.

6.4 Risk management and HSE incidences 2015

Pre-survey assessment of the risks associated with the mobilization and demobilization, operation or equipment, and their mitigations, are shown in Table 12. Likelihood and severity is rated on a scale from 1 to 5, 5 being the most likely or most severe. The risk is the product of the likelihood and severity.

Operation/ Event	**Risk:**	**Consequence:**	**Man-days of exposure**	**Likeli-hood**	**Seve-rity**	**Risk**	**Mitigation:**	**Resi-dual risk**
Driving between stations, during survey or scale factor calibration	Collision with other road users or fixed objects. Driving off the road.	Personnel injury Vehicle damage Property damage	84	2	5	10	Keep safe speeds and comply with speed limits. Follow road signs closely. Keep driver's attention high. Avoid distractions (phones, food, etc.) whilst driving. Do not drive while tired. Communicate and get support from second person in car. Change driver if needed. Acceptance for saying "stop", and call for an additional driver or halt the operation if necessary. Crew-change in the middle of the night (1 a.m.), giving 2-3 hours of daylight for both evening and morning shifts. Keep instruments, computers and batteries fastened during transport. First-aid equipment in the car. Minimum training of all personnel. Defensive driving training of all crew with a professional Dutch provider. A phone in the the car, with pre-registration of emergency number 112 for ambulance, fire brigade, police and Quad emergency number. Toolbox talks before crew change/job start to discuss any precautions for the measurements to be acquired on the oncoming shift (what are the difficult sites if any, execution plan). Actively use the road safety assessment of ANWB/EuroRAP for identifying risky parts of (main) roads and increase the drivers attention. Pay particular attention when driving through villages. Avoid village roads if an alternative with less pedestrians or cyclists is available nearby. Pay particularly attention just before schools start in the morning and after they end in the afternoon. Use two car navigation systems (TomTom and Google Maps) simultaneously in the car (both day and night), to avoid misunderstanding the path forward.	5

Operation/ Event	Risk:	Consequence:	Man-days of exposure	Likeli-hood	Seve-rity	Risk	Mitigation:	Resi-dual risk
Same as above, during nighttime	Same as above, but exacerbated by nighttime operations, both because of decreased visibility at night and because of fatigue from operating throughout the night.	Same as above	56	2	5	10	Make good lighting available for instrument deployment (headlamps and standing lights). Personnel should wear reflective clothing. Reflective traffic cones should be deployed if measurement site is close to road that might have nighttime traffic. Where feasible, schedule especially secluded or dark sites or sites located on poorly marked roads to be surveyed during daytime operations. If possible, mark measurement sites with reflective tape to make finding them at night simpler. Require two persons in vehicles at all times to help prevent driver from falling asleep. Have enough coffee on thermos in the car in the nighttime. Plan for slower progress at night hours, to not push the crew. Make a survey plan that minimize driving distance at narrow, dark roads at night. Allow more time for driving between stations at night. Pay particular attention in the first hours after darkness, when pedestrians and cyclists are more likely to be on the road.	5
Transporting (mostly hand-carrying) instruments from car to station or back	Equipment slips and falls to the ground.	Personnel injury on foot/leg, back injury or hand/finger injury. Muscle strain Damage to instrument.	84	2	2	4	Keep operators attention high. Good work-light during nigth-time, either attached to car or on a separate stand. Apply good ergonomic carrying methods. Use safety shoes, reflective vest and gloves. Toolbox talks before survey start on how to carry the instruments.	3
Parking car at station	Car hitting seismic station (at night)	Damage to seismic station	84	1	2	2	Put reflection band around the instrument box. Keep a parking distance of at least 5 meters.	2
Parking car on soft soil at station	Car sinking into soil.	Need assistance to get up on solid surface road.	84	1	1	1	Pay attention to site description and weather condiditons, particularly heavy rainfalls.	2
Making measurement inside fence of NAM-site	Car or equipment hitting facility	Damage to gas production facility					Follow NAM safety rules.	
Site measurement	Laptop or other equipment gets water intrusion	Laptop or other equipment fails	42	2	1	2	Waterproof equipment. Rain shield of equipment.	2
Site measurement	Man falling in dike at night	Personnel injury	84	1	1	1	Communication between the two operators at all times. Detailed map of each site.	1
Site measurement	Dog attack	Personnel injury	84	1	1	1	Go away from the site and report to the NAM responsible. Proper PPE (coveralls, gloves).	1
Install current supply from batteries	Terminals get shortened with a metal object which is in contact with an individual's skin.	Severe burns	14	1	2	2	Caution must be used when handling large batteries. Jewely (watches with metal bracelets and rings) should be removed.	2
Charging batteries	Generation of hydrogen gas	Flames, explosion	14	1	2	2	Good ventilation when charging batteries in the garage.	2

Operation/ Event	Risk:	Consequence:	Man-days of exposure	Likeli-hood	Seve-rity	Risk	Mitigation:	Resi-dual risk
Travel and shipment to/from the Netherlands	Human strain, accident, rough handling	Health problem, injury, equipment damage	18	1	3	3	Use recognized airlines and freight carriers. Resting hours and the longest ferry route for driver from Norway.	2
Site measurement	Angry / aggressive local people	Damage to equipment. Stress leading to operator errors	84	1	2	2	Stop working immediately, keeping the personnel and equipment safe Present the reference letter provided by NAM. No further discussion nor argument. Contact Wim van der Veen or Shizhuo Liu in NAM to report the situation. Accomapying person that speaks the local dialect, may explain that we are doing. Leave the site and move on the the next site	2
Scale factor calibration measurement	Collision with other road users or fixed objects. Driving off the road.	Personnel injury Vehichle damage Property damage	2	2	5	2	Sufficient rest before the work starts. Person (Mark) flying in from US arriving a day before will have a business class seat, to facilitate a good sleep on the plane. Ola will be replacement in case Mark or Joel feels tired at start-up. They will vary thed drivers position.	
Absolute gravity measurement with FG-5	Transport of boxes.	Damage to equipment Personnel injury	3	1	1	1	Sufficient people to carry boxes onto the site.	1
Absolute gravity measurement with FG-5	Setting up the instrument in a new environment	Damage to equipment Personnel injury	3	1	1	1	Tidy-up the site prior to the measurement. Checking out the site carefully before installing the instrument.	1

Table 12: Risk assessment.

All foreign crewmembers went through half a day of defensive driving training, provided by VVCR (https://www.vvcr-international.com/). It consisted of a theoretical introduction and practice with the survey car on the roads in the survey area. The crew found this useful.

All sites were visited by Quad prior to the survey, in order to assess risk, and make maps and site descriptions.

Helmet, glasses, gloves, safety shoes or boots, coverall (antistatic and flame retardant) were carried inside all NAM sites. Gas detection sensor was provided by NAM. Safety shoes or boots, coveralls and gloves were used at the non-NAM sites.

Reporting lines for emergency accidents and incidents were as shown in Figure 46. On NAM sites, any incidents were to be reported immediately to the site HSSE (Health, Safety, Security and Environment) focal point or emergency center. If it involved personnel injury, it should also be reported to the NAM representative (working hours) or duty surveyor (at nights) as early as possible. The two incidents experienced were reported in a following daily report and call to the company representative.

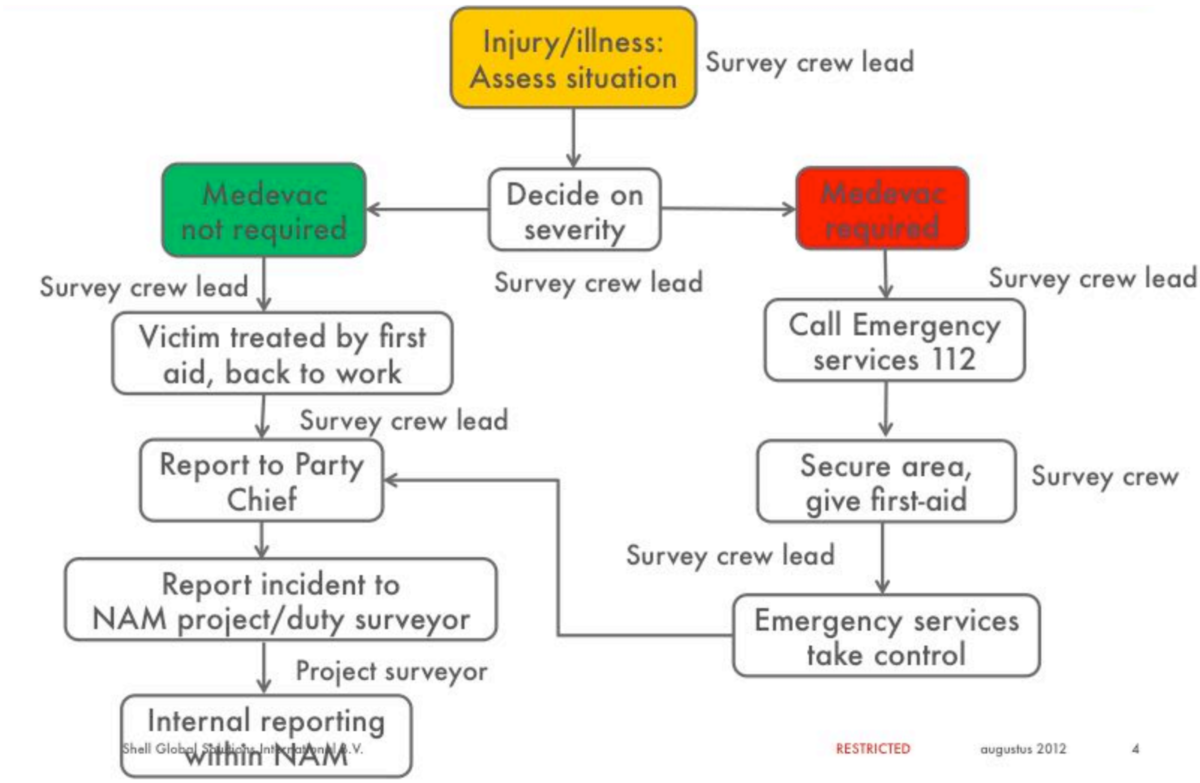

Figure 46: Flowchart for emergency and incident reporting.

Two incidents were reported during the 2015 data acquisition.

On September 23rd at 19:15 local time, on site #101, a damage to Quad equipment occurred. A coffee thermos fell out of the survey vehicle. The interior glass liner shattered, contents spilled and broken glass remained inside the thermos. It was caused by the device not properly constrained in the vehicle. The thermos was safely discarded, including the glass contained coffee. A new metal thermos was aquired, and it was better secured in the vehicle. The incident was reported by Michael Davis.

On September 27th at 14:00 local time, on site #514, the survey car got stuck in soft field. This occurred after driving into the soft field, when trying to turn around and return to paved road. The crew first tried to use gravel to gain traction, but it did not work. Then a tow truck was called, which pulled out the survey car. Proposed measures to prevent similar incidents in the future are to scout the field better to see how soft it is, and possibly to use better tires for off-road, or a 4-wheel drive car. The incident was reported by Joel White.

6.5 Acquisition of 2015 survey gravity data

The main survey started September 13th at 09:00 and was completed September 27th at 03:20 (local time). Altogether 309 measurements were done, and all stations were visited at least three times. The network map of station visits is shown in Figure 47.

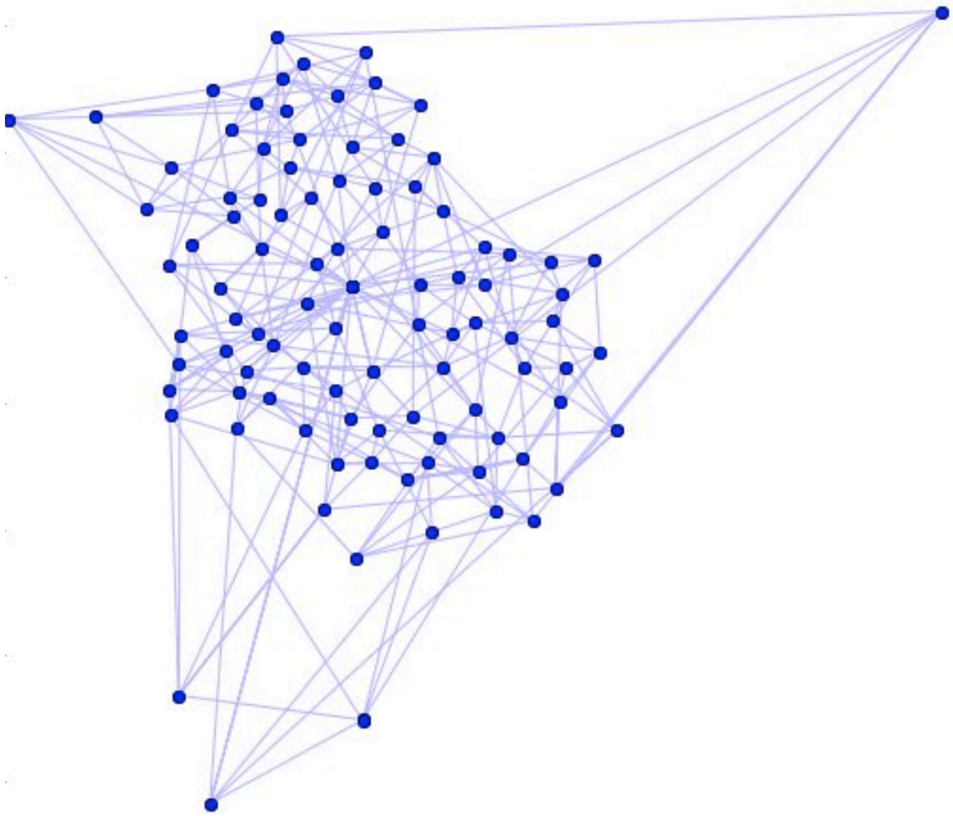

Figure 47: Map of stations, with a straight line drawn between subsequent measurements.

Based on the various CG5 unit performances during the calibration and transfer surveys, units 10, 12 and 13 were put into use initially, with unit 11 on hold. Unit 12 failed on September 15th, and was immediately replaced by unit 11. The fault was identified the same evening, a circuit board was replaced and the meter was again ready for use. Unit 12 was put back into service September 21st, when unit 11 started to give bad signals intermittently, and it worked well through the rest of the survey.

Damping mechanisms in the transport racks protected the instruments from shock and vibration during driving. The operators gently hand-carried each unit from the car to the site, with no incidences reported. Power supply was run through cables for the stations that were within reach. For more than 12 m distances, the instruments were run on internal batteries during the measurement. Commands and data were all the time transferred wireless. Data were recorded continuously for 20 minutes. When raining, plastic covers were used to shield the units. Data were loaded onto USB memory drives at the end of each shift and brought to the office/hotel in Ten Boer for subsequent safe copying and processing. Editing of new records and updated drift inversions were performed at about 7 am, 10 am and 6 pm every day.

On the short side of the seismic stations, the three meters were put side-by-side (Figure 30) in a sequence such that unit numbers increased towards the right when looking at the station.

The 309 measurements were completed in 13 days 17 hours and 10 minutes, averaging 22.5 measurements per day, or 1 hour and 4 minutes per measurement. This is somewhat faster than the pre-survey expectation of 20 measurements per day. The progress was steady, as seen in Figure 48 and Figure 49. Small delays were caused by unit replacements (two times), and slower than average progress occurred for every long drive to a reference station (Aurich, Westerbork, Kloosterburen).

Station #404 in the Overschild windmill was used as central reference station. Each loop started and ended here. Altogether 14 measurements were made at #404 – approximately once a day. All other stations received 3 measurements, except #140, 169, 303 and 518 which received a 4th visit.

Slow traffic from farming trucks during harvesting was flagged as a possible issue, but no problems were encountered. Some hints of fog were encountered during nights with a clear sky, but the fog did not reduce visibility enough to increase the risk or cause driving problems.

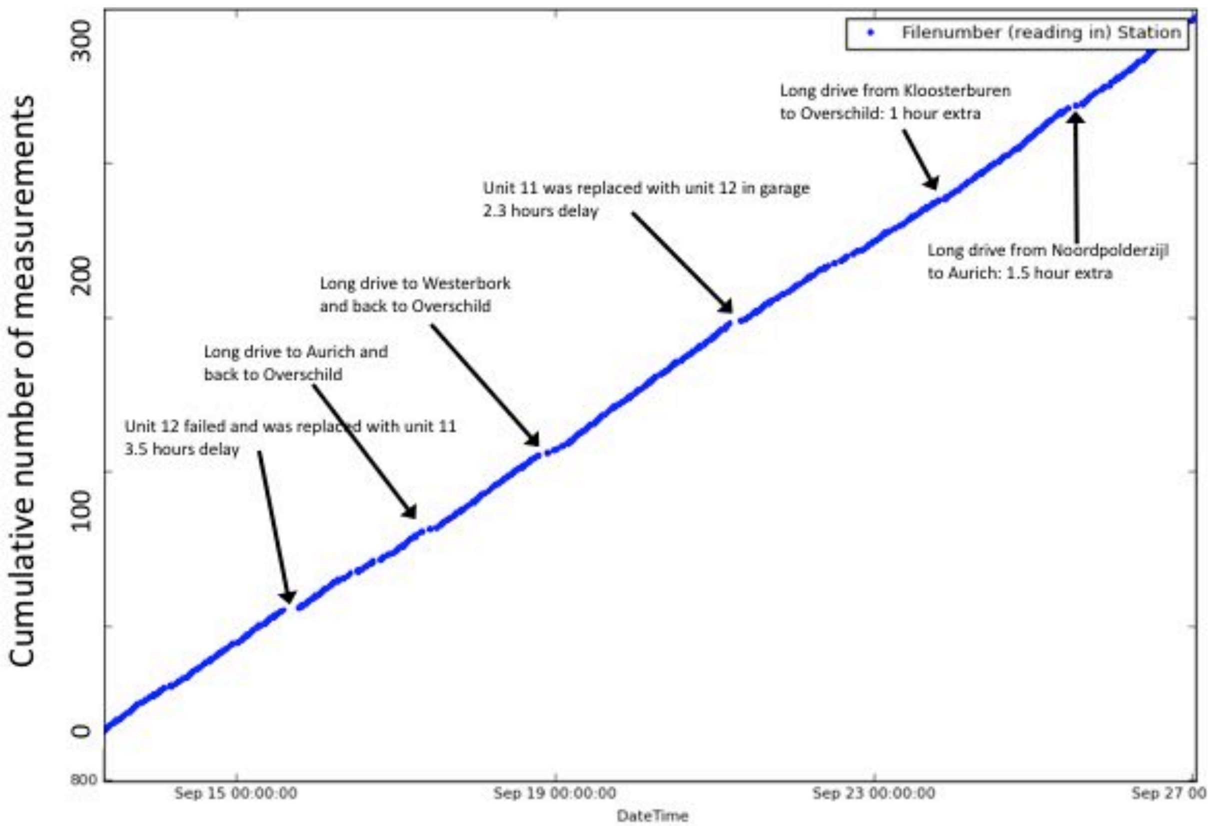

Figure 48: Survey progress, shown as cumulative number of measurements vs. running time.

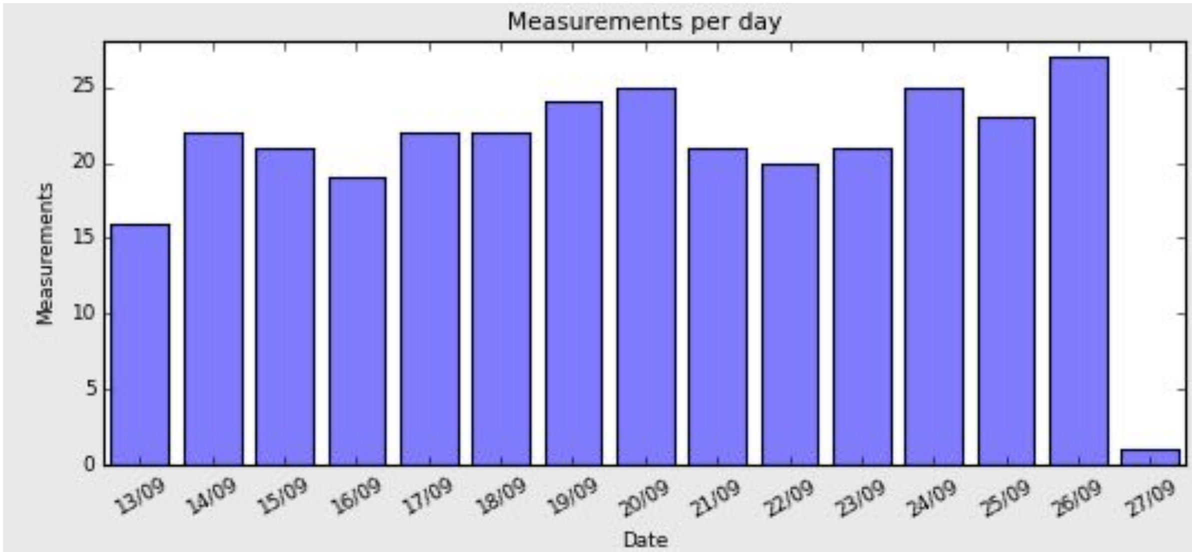

Figure 49: Number of measurements per day (midnight to midnight UTC).

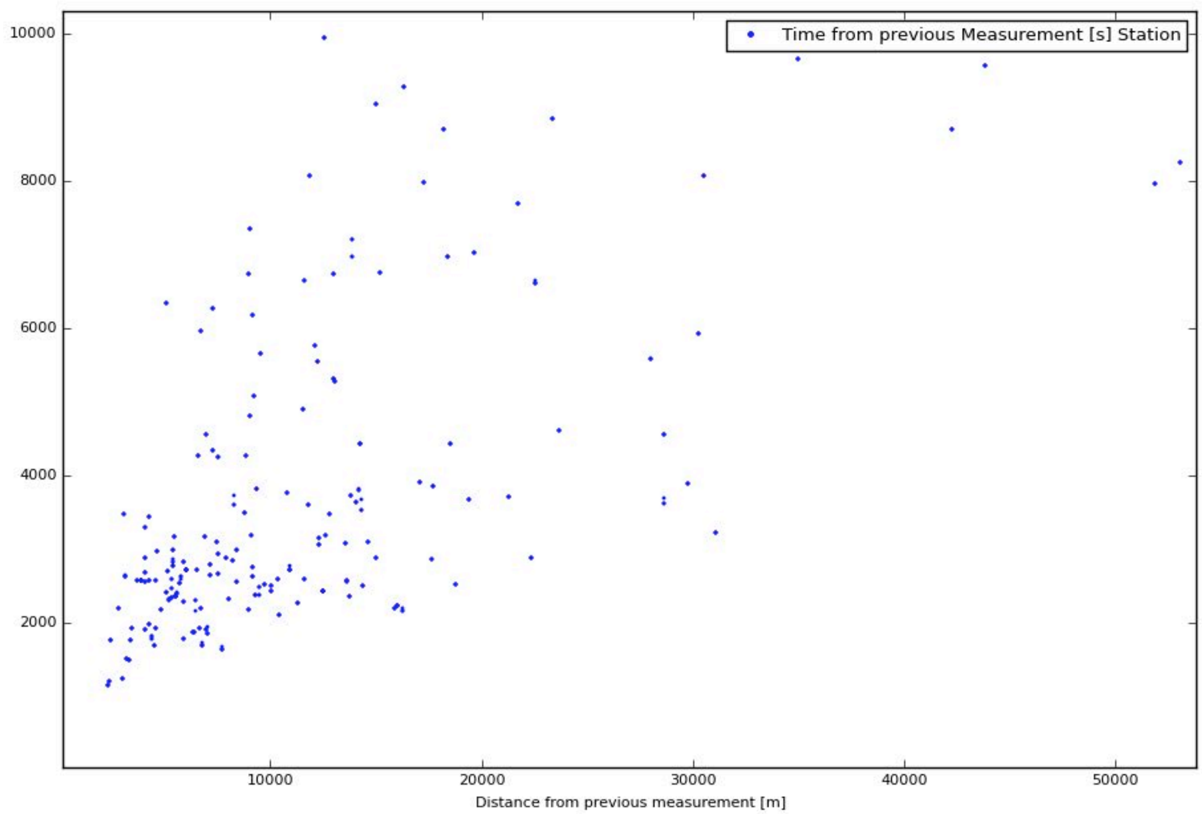

Figure 50: Time between measurements (in seconds) vs. distance between stations (straight line in meters).

The time between measurements is cross-plotted against distance in Figure 50. While there clearly is a relation, the scatter is large. The GPS tracking of the car for the last 11 days is shown in Figure 51. A variety of large and small roads were used.

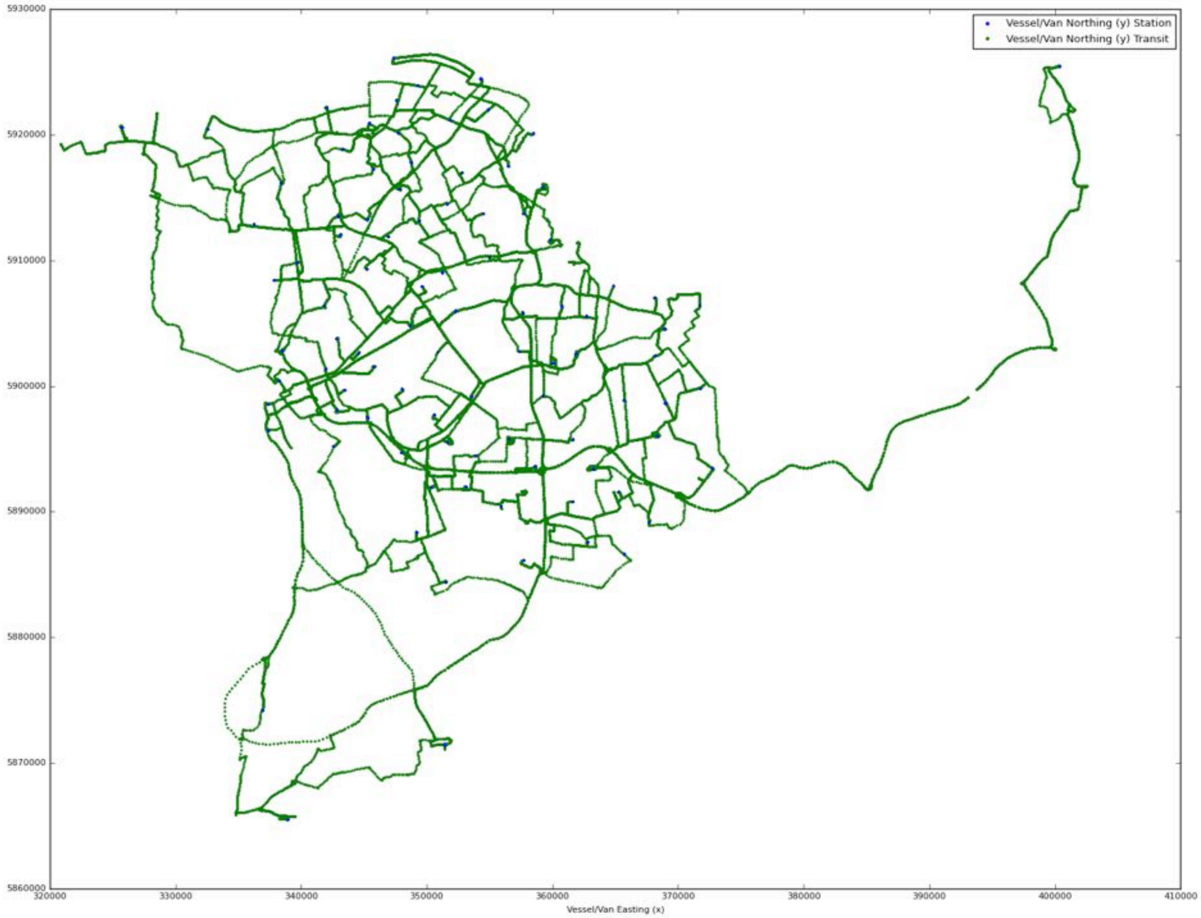

Figure 51: Vehicle position data for most of the survey (from September 16th to the end of the survey).

The gravimeters were protected from the sunshine by an E-Z Up tent or in some cases an umbrella (Figure 52). The tent worked fine in the moderate wind conditions experienced. The tent or plastic covers (Figure 53) were used to protect the gravimeters from rain.

The operators noted all events in a hand-written logbook, filled with 86 pages at the end.

Figure 52: Pictures of tent and umbrella used for shelter against the sun.

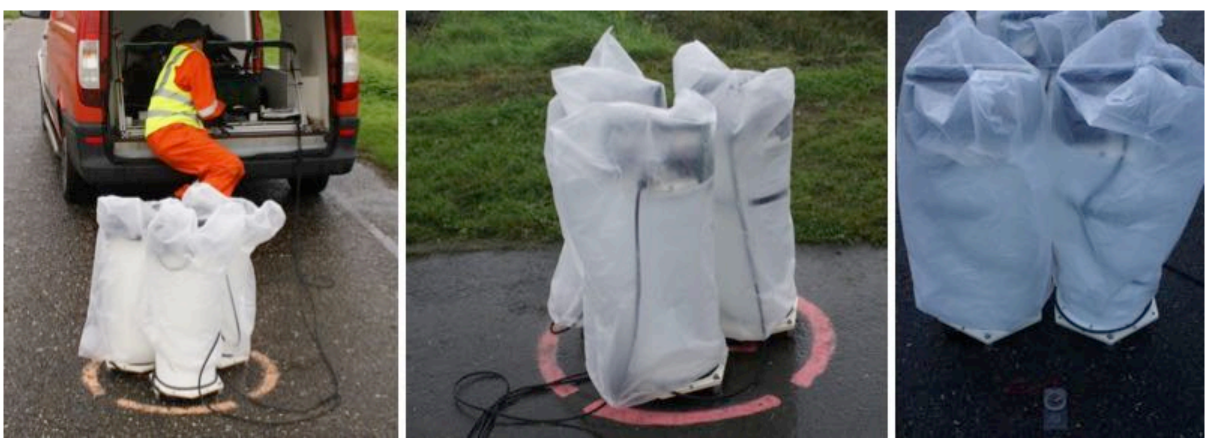

Figure 53: Pictures of plastic covers used for protecting the top electronics against heavy rainfall.

7 Environmental data

Environmental data have been recorded and stored by Koninklijk Nederlands Meteorologisch Instituut (KNMI) for all surveys at the station Eelde (found at http://www.knmi.nl/nederland-nu/klimatologie). For 2015, three KNMI stations; Eelde, Lauwersoog and Nieuw Beerta (locations seen as yellow stars in Figure 54) were used. Hourly averages have been recorded at the KNMI sites for more than ten parameters related to air temperature, wind speed, humidity, cloud cover and sunshine and precipitation. Air pressure and temperature was also recorded in 2015 by Quad's sensors. The most important parameters influencing the gravity acquisition are presented in the following sections.

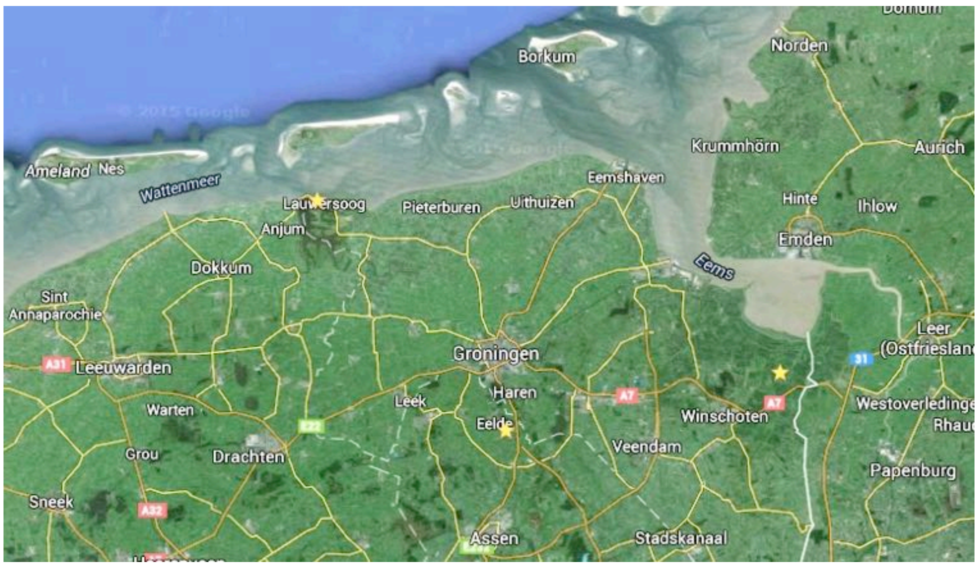

Figure 54: Map of the area with the three public (KNMI) weather stations marked as yellow stars.

7.1 1978 survey

Heavy rainfall occurred a few days into the survey (September 29th and 30th), with an associated 10 hPa drop in air pressure (Table 13). Temperature fluctuations (minimum-maximum) exceeded 10°C for the last part of the survey, caused by a period of sunny days and cold nights.

Month	Date	Rainfall	Temperature			Air pressure	Wind (average)	Humidity	Sunshine	Clouds
			Average	Maximum	Minimum					
		[mm]	[°C]	[°C]	[°C]	[hPA]	[m/s]	[%]	[hours]	[1/8'ths]
September	25th	3.7	13.0	16.0	7.0	1017.4	5.7	91	1.4	5
	26th	0.9	10.5	15.9	6.3	1018.8	4.6	91	4.4	4
	27th	6.8	9.9	13.6	5.5	1011.7	4.1	95	2.1	6
	28th	2.5	10.0	15.0	6.1	1010.8	3.1	88	3.9	6
	29th	15.9	11.6	16.0	9.2	999.9	5.1	92	2.9	7
	30th	11.5	9.7	11.1	8.7	998.2	4.6	95	0.2	7
October	1st	2.1	10.0	13.0	6.8	1012.8	6.2	89	2.9	6
	2nd	0.0	8.3	10.7	5.4	1022.1	1.5	93	0	7
	3rd	0.0	7.6	11.8	3.5	1019.2	1.5	93	3.6	6
	4th	1.5	8.7	14.2	3.4	1018.5	3.6	89	5.6	5
	5th	0.7	12.0	15.5	6.4	1017.4	8.2	92	0	7
	6th	0.1	14.1	16.4	9.9	1020.8	6.2	93	0	7
	7th	0.0	12.4	17.8	7.0	1022.9	1.5	93	2.4	4
	8th	0.0	11.4	18.5	4.5	1018.1	2.1	91	6.5	1
	9th	0.2	13.5	17.5	9.3	1017.3	2.6	94	0.7	6
	10th	0.0	15.5	20.8	10.9	1019.7	2.1	92	5	5
	11th	0.0	15.6	23.7	10.1	1024.9	2.1	85	9.3	2
	12th	0.0	14.2	21.5	7.4	1026.8	2.1	85	9.4	1
	13th	0.0	12.8	20.8	6.7	1022.9	1.0	89	8.6	2

Table 13: Key weather data for the 1978-survey (from KNMI).

7.2 1984 survey

This survey had generally good summer weather (Table 14), with moderate precipitation and fairly stable air pressure. June 19th-21st had much sunshine and maximum temperatures up to 26°C.

Month	Date	Rainfall	Temperature			Air pressure	Wind (average)	Humidity	Sunshine	Clouds
			Average	Maximum	Minimum					
		[mm]	[°C]	[°C]	[°C]	[hPA]	[m/s]	[%]	[hours]	[1/8'ths]
June	6th	0.8	11.0	14.3	4.8	1008.2	5.1	91	0	7
	7th	1.8	11.8	13.4	10.0	1005.4	2.6	99	0	7
	8th	0.0	11.3	13.9	8.0	1008.8	4.6	92	1.3	6
	9th	0.1	11.5	14.3	9.7	1015.4	6.7	87	2.2	7
	10th	0.0	11.1	14.4	9.0	1022.0	3.6	85	0	8
	11th	0.0	10.9	16.2	4.7	1027.3	3.1	78	11.5	3
	12th	0.0	13.3	19.3	4.6	1025.3	3.1	77	11.2	5
	13th	3.7	14.4	16.0	12.6	1019.3	6.7	95	0	8
	14th	8.1	13.5	16.0	10.8	1017.9	6.7	88	2.6	7
	15th	0.1	11.7	14.5	10.4	1023.0	5.7	92	0	8
	16th	0.2	11.8	13.9	10.3	1023.7	3.6	88	0	8
	17th	0.0	13.3	17.2	11.5	1023.3	4.1	87	3.3	7
	18th	0.0	13.3	17.2	11.5	1023.3	4.1	87	3.3	7
	19th	0.0	16.8	24.2	8.1	1027.4	2.1	82	10.9	1
	20th	0.0	19.6	26.5	9.7	1018.5	1.5	78	11.8	2
	21th	0.0	15.9	22.6	7.6	1010.8	5.1	83	7.4	4
	22th	2.4	12.7	15.9	7.1	1008.5	6.7	90	0	7
	23th	0.7	11.3	14.8	9.2	1010.4	8.7	75	4.6	6
	24th	0.9	10.7	14.3	7.5	1014.7	7.2	78	4.7	6
	25th	4.1	12	15.3	6.6	1013.8	7.7	88	0.5	7
	26th	0	13.4	17.2	10.8	1020.4	6.7	83	2.3	7
	27th	0.1	13.2	18.4	8	1015.7	5.1	92	2.7	6
	28th	1.2	11	15.4	6.8	1013.1	5.7	87	3	5
	29th	10.3	10.5	15.6	6.2	1013	5.1	88	3.1	6
	30th	2.6	11.2	14.5	8	1015	6.2	85	5.1	6
July	1st	0	12.1	16.4	9.6	1018.9	3.1	79	7.8	6
	2nd	7.5	10.8	14.2	8.3	1013.8	3.6	95	0	7
	3rd	2.3	11.4	14.1	7.9	1019.8	6.2	91	0.1	7

Table 14: Key weather data for the 1984-survey.

7.3 1988 survey

This was an early summer survey, with two days of heavy rainfall (May 31st and June 8th), as shown in Table 15. There were a few sunny days, with maximum temperature just above 20°C.

Month	Date	Rainfall	Temperature			Air pressure	Wind (average)	Humidity	Sunshine	Clouds
			Average	Maximum	Minimum					
		[mm]	[°C]	[°C]	[°C]	[hPA]	[m/s]	[%]	[hours]	[1/8'ths]
May	30th	1.3	14.1	20.9	8.6	1004.4	5.1	76	7.4	5
	31st	19.7	13.2	18.4	7.7	1006.1	6.7	92	3.0	7
June	1st	5.8	14.7	20.0	8.5	1010.0	6.2	85	6.8	5
	2nd	5.9	13.5	18.2	8.2	1013.5	4.6	89	3.3	7
	3rd	2.5	14.6	18.6	10.4	1008.2	6.2	75	7.2	6
	4th	1.9	12.0	17.3	7.2	1006.9	4.1	85	3.5	5
	5th	0.6	11.4	15.9	6.5	1015.8	4.1	82	5.7	5
	6th	0.0	11.9	15.2	8.0	1019.4	4.1	78	0.5	7
	7th	1.7	13.4	15.3	11.3	1014.8	3.1	97	0	8
	8th	20.2	14.5	16.4	13.2	1016.9	2.6	98	0	8
	9th	2.2	14.8	16.3	13.5	1016.4	2.6	100	0	8

Table 15: Key weather data for the 1988-survey (from KNMI).

7.4 1996 survey

This survey took place in winter time, with cold and clear days, temperatures well below 0°C, during the first four days (Table 16). There was only one day of significant precipitation, and it is not clear whether some of this was laying as snow on the ground. Particularly high air pressure was experienced on the 14th and 15th of February.

Month	Date	Rainfall	Temperature			Air pressure	Wind (average)	Humidity	Sunshine	Clouds
			Average	Maximum	Minimum					
		[mm]	[°C]	[°C]	[°C]	[hPA]	[m/s]	[%]	[hours]	[1/8'ths]
February	6th	0.0	-7.8	-3.9	-10.4	1005.1	5.7	83	8.3	3
	7th	0.0	-9.0	-6.7	-12.1	1002.0	6.7	68	5.5	5
	8th	0.0	-10.4	-7.7	-13.5	1012.6	4.1	76	6.8	6
	9th	0.0	-9.8	-4.7	-15.6	1018.4	4.1	82	6.0	5
	10th	0.5	-0.4	3.0	-4.7	1008.9	5.1	90	0.0	8
	11th	2.8	2.8	3.6	2.2	1006.1	5.7	98	0.0	8
	12th	15.2	2.2	3.6	0.2	993.7	5.7	98	0	8
	13th	0.8	0.2	0.6	-0.2	1004.7	7.2	98	0	8
	14th	0.0	-1.5	-0.2	-2.9	1029.8	4.6	89	0	8
	15th	3.7	-0.5	3.4	-4.6	1029.5	6.2	93	0	8
	16th	1.6	4.6	6.8	3.1	1013.7	7.7	93	0.4	7
	17th	0.8	3.6	6.1	1.2	1009.1	9.3	88	2	7

Table 16: Key weather data for the 1996-survey (from KNMI).

7.5 2015 survey

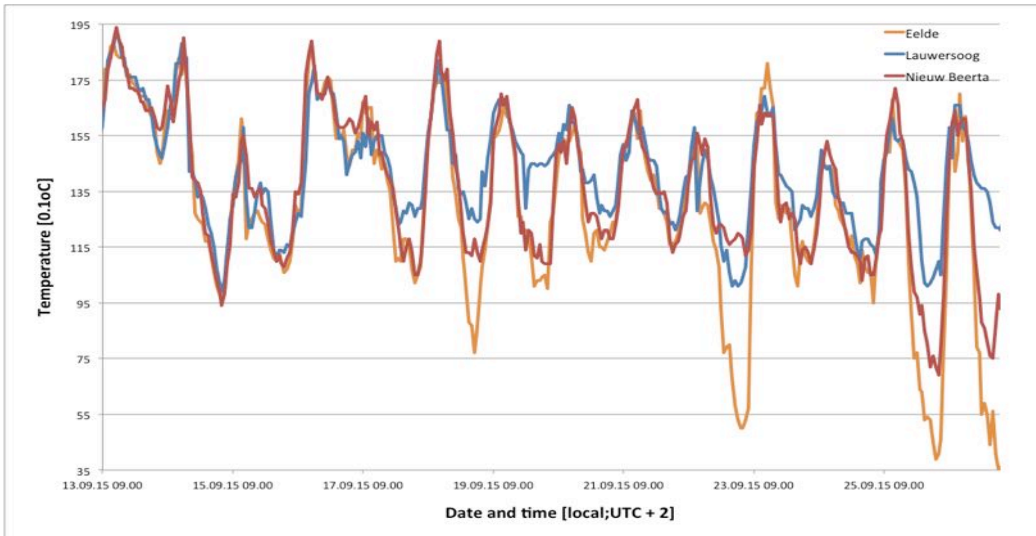

Figure 55: Air temperature during the survey period (hourly averages) as recorded on Eelde, Lauwersoog and Nieuw Beerta stations (data from KNMI).

Ambient air temperatures varied between 3.5°C and 19.5°C during the survey period. Day-night variations were from 4°C and up to 13°C (Figure 55). Some significantly colder nights were recorded at Eelde, probably due to the more inland position of this site. Night temperatures were slightly higher than expectations for the season (Table 17) for most of the surveys, with 5 nights of low temperature, particularly away from the coast (Eelde). Day-night contrasts were on average slightly less than the 9°C expected.

Date	Mean T [°C]	Maximum T [°C]	Minimum T [°C]	Sunshine [hr]
September 12th	13.8	18.5	9.1	4.7
September 27th	12.9	17.6	8.5	4.0

Table 17: Expected mean, maximum and minimum temperature for Groningen in the month of September.

The temperature on a sensor sitting inside the vehicle is shown in Figure 56. The diurnal variations are easily seen, with amplitudes of mostly 5-7°C. Some short duration 'spikes' of high temperature probably corresponds to periods of direct sunshine on the sensor through an open door.

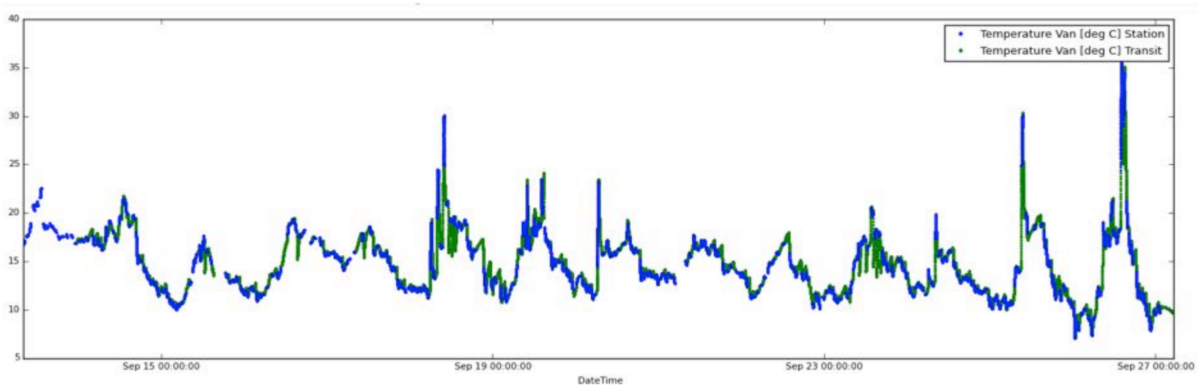

Figure 56: Temperature inside the back of the survey van, in °C. Blue color during measurements and green color during transits.

The temperature recorded by a sensor attached to the outside of one of the gravimeter units is shown in Figure 57 together with the van temperatures. The co-variation is strong.

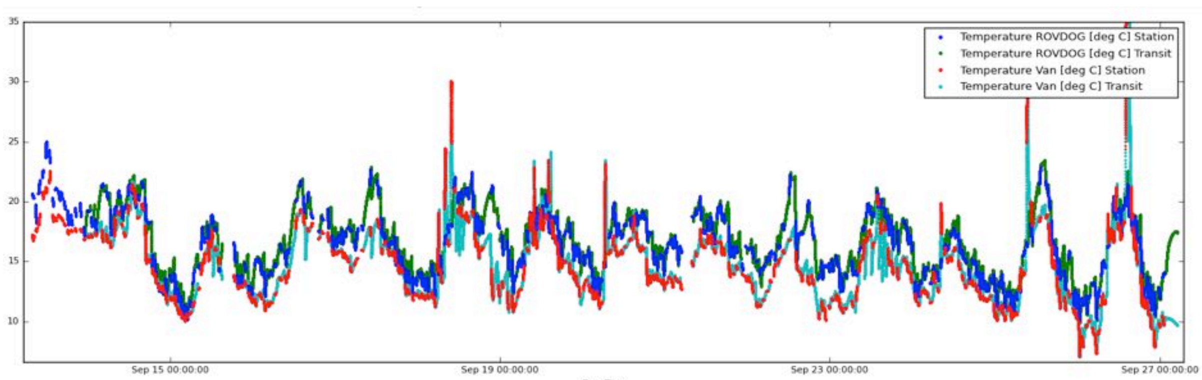

Figure 57: Temperature outside the gravity unit (blue color during measurements and green during transits) and inside survey van (red color during measurement and light blue during transits), in °C.

The temperature sensors inside the aluminum case of the gravity units are shown in Figure 58. The same diurnal pattern is recognized, but with slightly smaller amplitude, mostly 4-6°C.

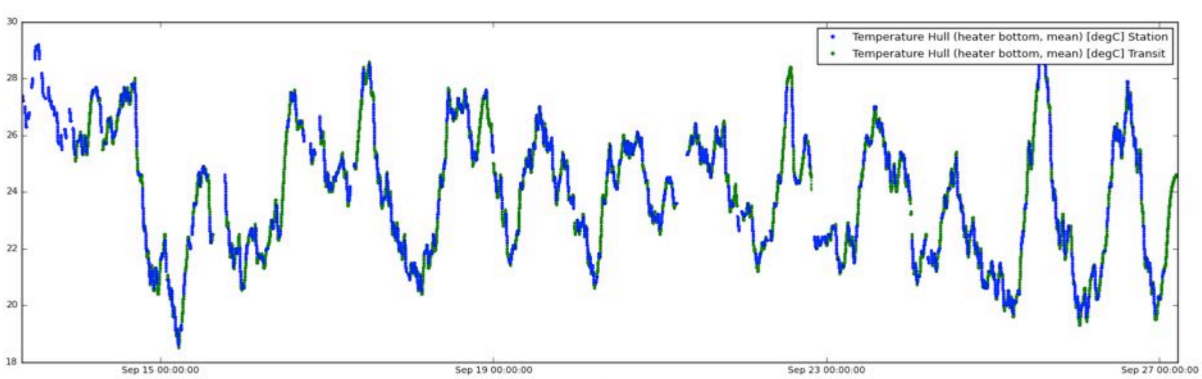

Figure 58: Temperature inside the aluminum case surrounding the CG5, in °C.

Finally, the CG5 sensor temperatures are shown throughout the survey period (Figure 59). Fluctuations are now in mK. These temperatures show little correlation with the surrounding temperature (Figure 60), but a strong dependency on where in the recording cycle the sensor is. The sensor temperature drops by 0.2-0.5 mK during a measurement, and rises a similar amount during the transit to the next station. The cause of this is not clear, but may be related to internal heat generation during strong movements.

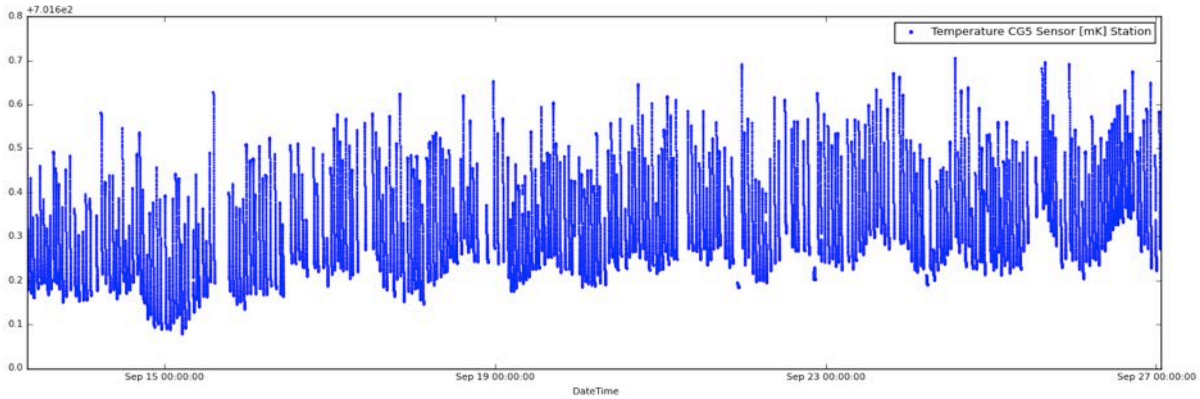

Figure 59: CG5 sensor temperature (of unit 10) during all measurements, in mK.

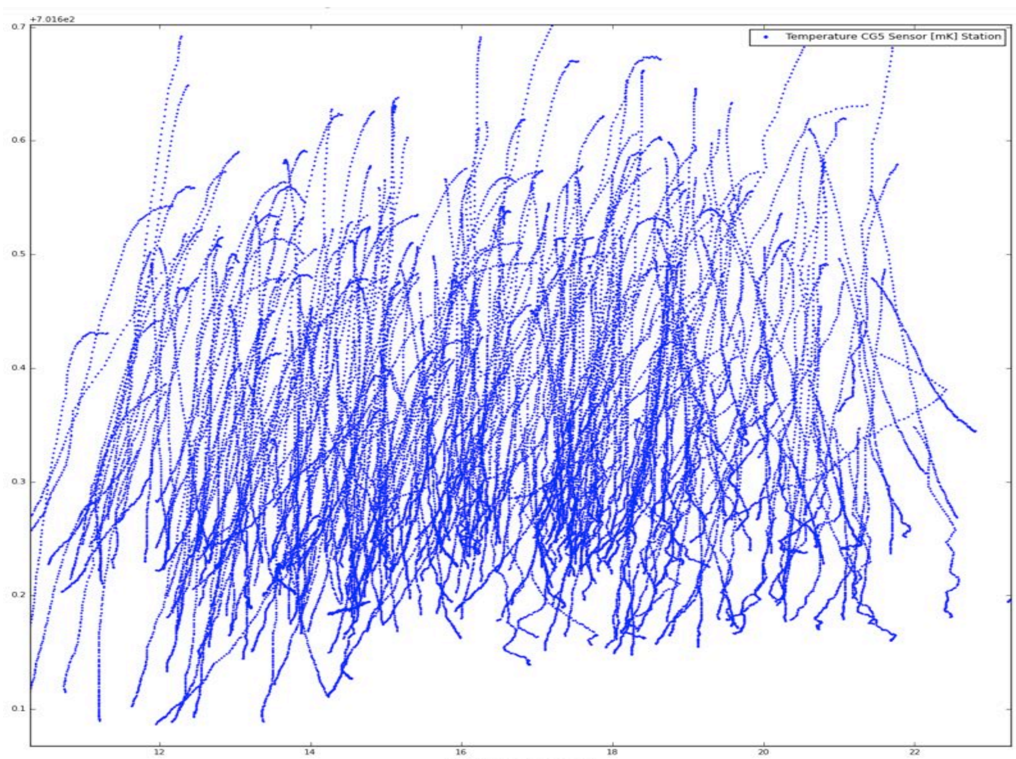

Figure 60: Cross-plot of CG5 sensor temperature (y-axis) and the sensor placed outside the gravimeter unit.

The amount of daily sunshine varied through the survey period as shown in Figure 61. Sunshine heats up the instrument cases, and a tent provided protection.

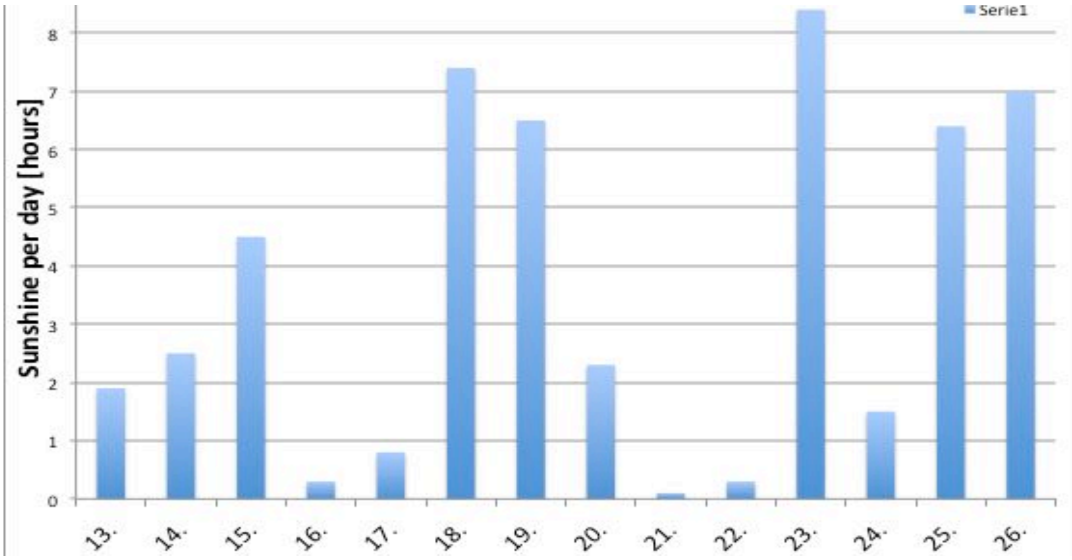

Figure 61: Sunshine for the survey days in September recorded on Eelde (KNMI).

Cumulative precipitation of about 21 mm occurred over the survey period (Figure 62). This was distributed over all days except the last two.

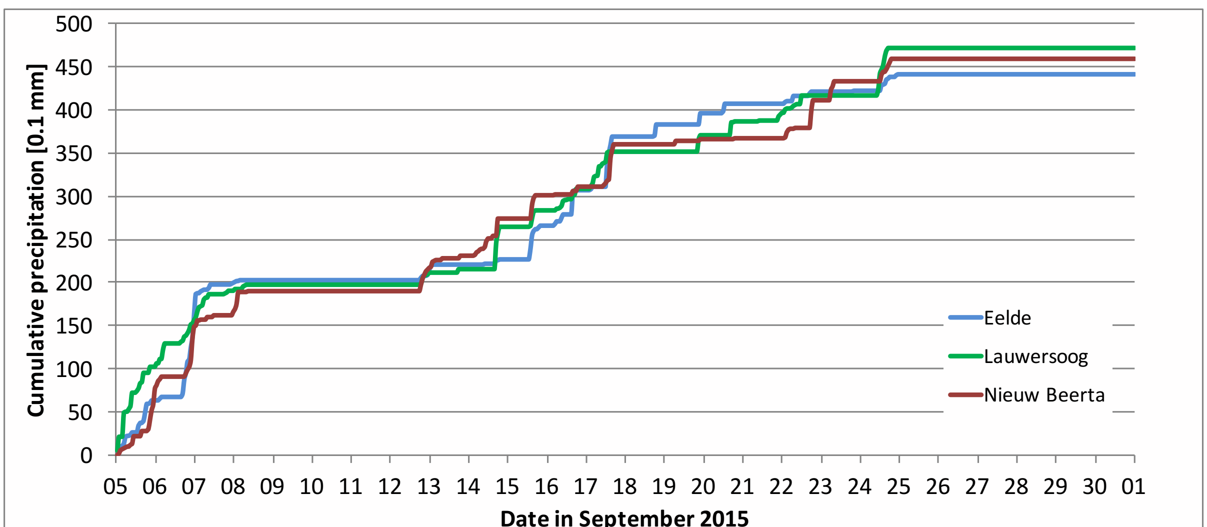

Figure 62: Cumulative precipitation starting September 5th, recorded on the three KNMI stations.

The three stations show very similar curves, suggesting the rainfall was evenly distributed throughout the area. Rainfall has also been measured by Watershap Hunze & Aas, at eight stations (Figure 63) covering a 32 km wide area (Figure 64a). They are close to scaled versions of each other, and we suspect this is due to some calibration error and not local variations in rainfall.

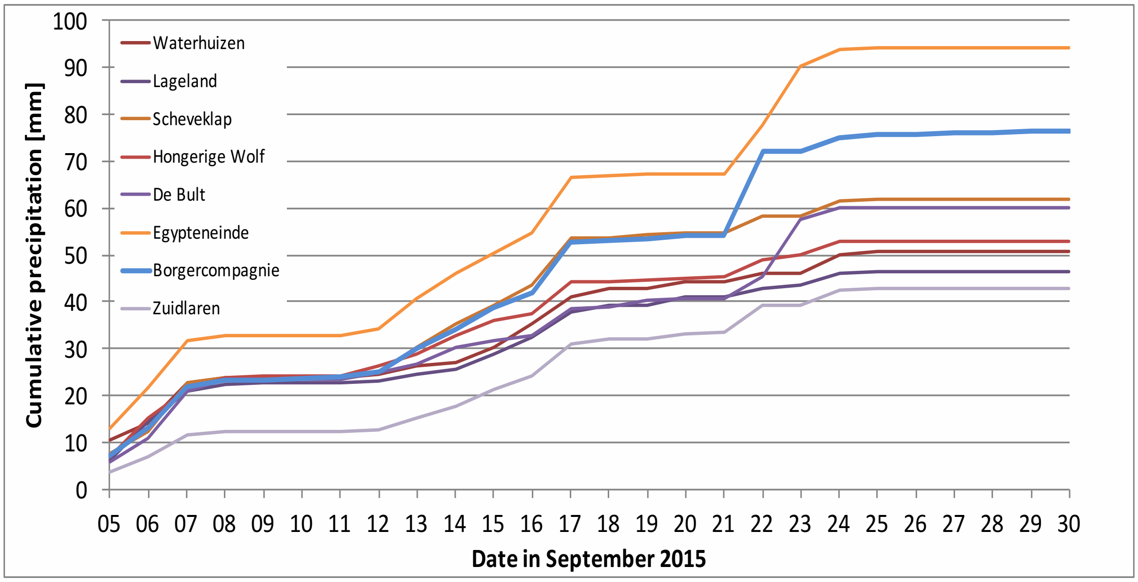

Figure 63:Cumulative precipitation at eight stations recorded by Watershap Hunze & Aas.

Waterschap Hunze & Aas describes their rain gauges as "an English setup"; where the rain gauge is placed in a raised pit of three meters in diameter with a floor of pebbles. The rain gauge does not protrude above the edge of the pit so that the wind has little influence on the falling precipitation and the measurements are more accurate. The amount of precipitation must be measured at least once per day to counteract the evaporation as much as possible.

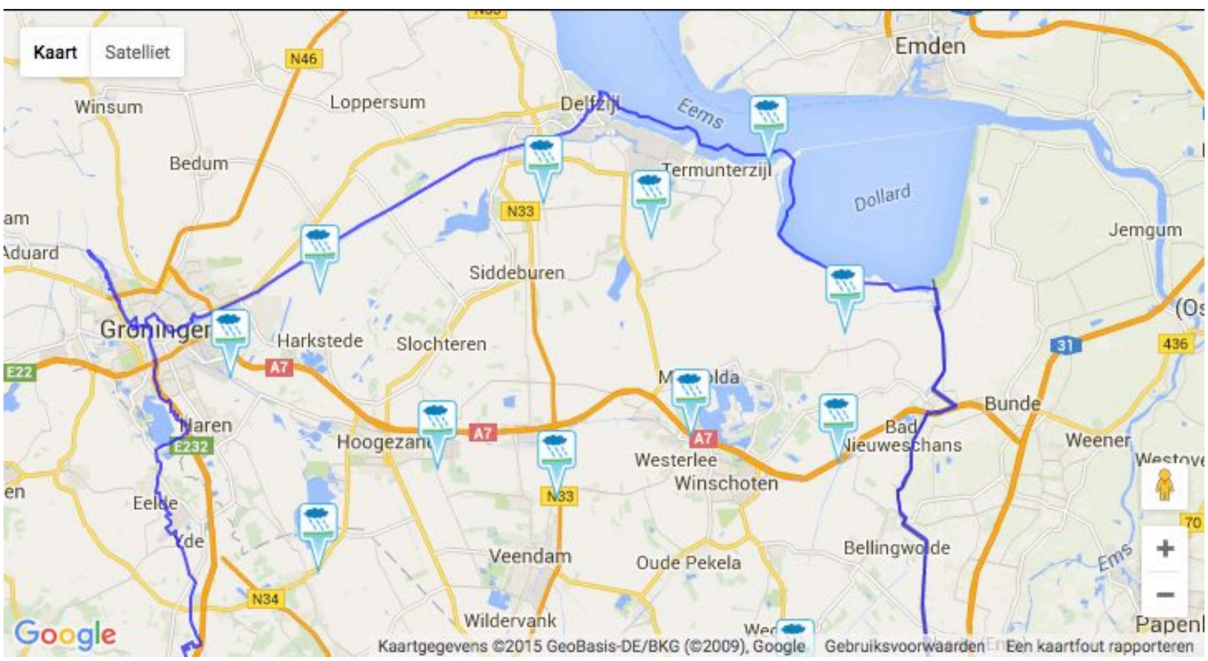

Figure 64: Map of rainfall stations operated by Waterschap Hunze en Aa's.

In the following, only the KNMI stations are used.

Air pressure varied between 989 and 1030 hPa in the survey period (Figure 65). Gravity corrections for air pressure variations are analyzed in section 13.4.

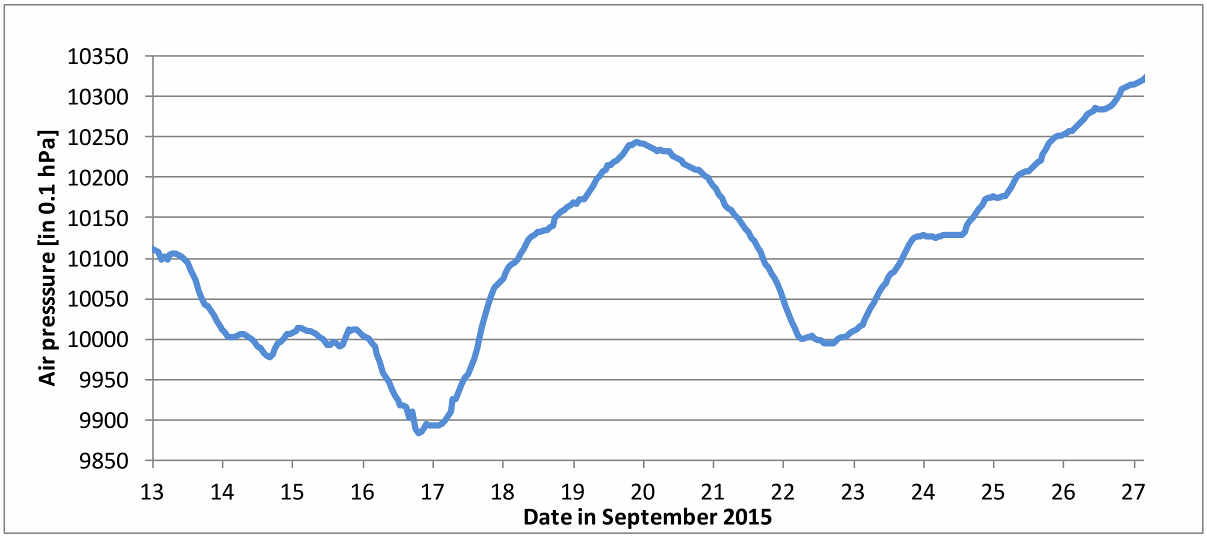

Figure 65: Air pressure as recorded on Eelde (KNMI).

8 Reference gravimeters

Two reference gravimeters were recording during the 2015-survey, in order to compare with the earth tide and ocean loading models used in the processing software. Any deviation between the data and the model may be used to improve the earth tidal model and thus the corrections. A gPhoneX rented from Micro-g LaCoste Inc, hereby called *gPhone*, and a Lacoste meter rented from Scripps Institution of Oceanography, hereby called *LaCoste/Scripps*, were stationary in the garage in Ten Boer during the survey for continuous recording. The sensors were inside thermally insulated spaces, together with temperature sensors. The gPhoneX recorded from September 13th at 00:00 to 27th at 12:43 UTC (Figure 66). Samples are missing September 15th between 14:30 and 23:59. The large excursions on September 17th was caused by an earthquake in Chile. The LaCoste/Scripps recording started September 12th at 15:20 and ended September 27th at 12:48 (Figure 67). The data must be scaled to µGal with scaling factor, to be determined. There are obvious periods of bad data in the early part of the record. The sampling rate was 1 s for both meters.

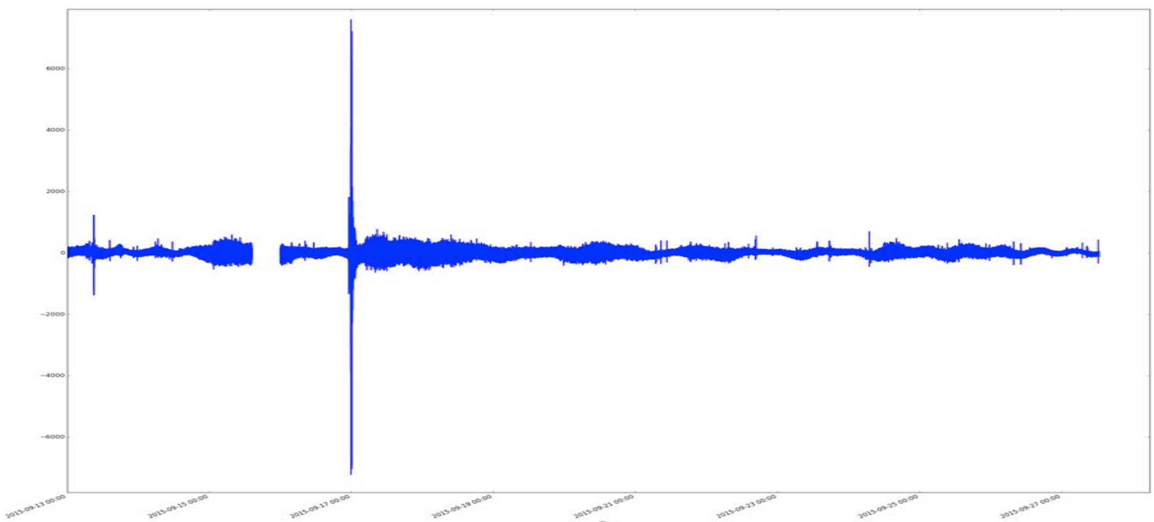

Figure 66: The complete gPhoneX gravity record, from 13th to 27th of September. The scale of the y-axis is µGal, and the total plot range is about 8000 µGal.

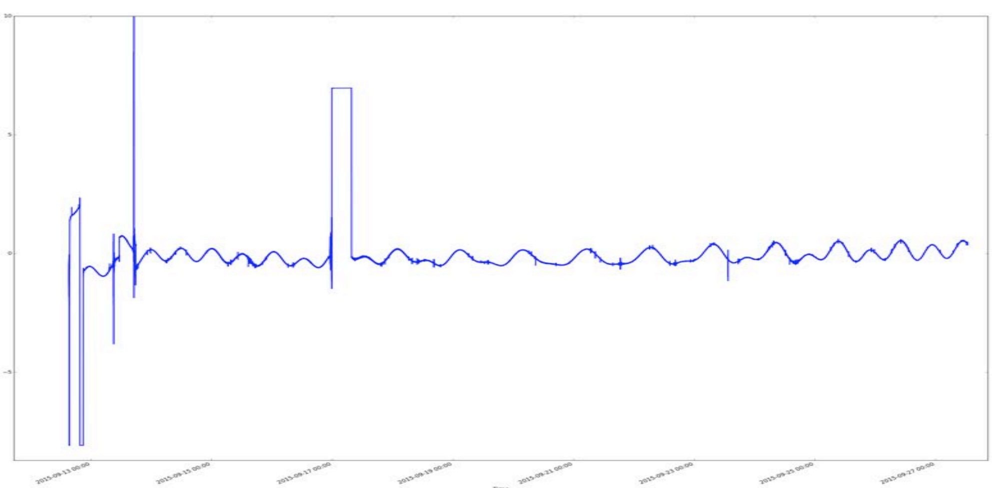

Figure 67: The complete LaCoste/Scripps gravity record. The scale of the y-axis is in Volts, with total range +/-10V.

Before the analysis of residual tides is possible, the gravity data must be corrected for sensor temperature effects, varying gravity attraction from air (air pressure effect), sensor drift, modelled ocean loading and modelled solid earth tides. All the corrections are subtracted from the raw data, i.e.

$$g_{residual} = S_f g_{raw} - g_{corrections}$$

Here, S_f is a scale factor, necessary to scale the data from volts to µGal for the LaCoste/Scripps data. The scaling is not required for the gPhone data, and is thus set to 1.

The corrections can be written as:

$$g_{corrections} = g_{ET} + g_{AP} + g_D + g_T + g_{OL}$$

where the subscripts denote solid earth tide (ET), air pressure (AP), drift (D), temperature (T) and ocean loading (OL) respectively. The solid earth tide and drift are by far the largest corrections. The gradual drift of the gravimeter is calculated from the data after the known corrections are subtracted, i.e. solid earth tide and ocean loading. The drift is calculated as a least-squares second order polynomial for the whole time series. For the Lacoste/Scripps data, the scale factor and drift is calculated simultaneously from a matrix equation, i.e.:

$$S_f g_{raw} = g_{res} + g_{corr} + g_{drift}$$

where:

$$g_{drift} = a + bt + ct^2$$

The matrix equation is then:

$$g_{raw} = \frac{Ax + v}{S_f}$$

with:

$$A = \begin{pmatrix} g_1^{corr} & 1 & t_1 & t_1^2 \\ \vdots & \vdots & \vdots & \vdots \end{pmatrix}$$

and:

$$x = \frac{1}{S_f}\begin{pmatrix} 1 \\ a \\ b \\ c \end{pmatrix}$$

The least-squares solution, minimizing the squared residual, $v^T v$, is:

$$x = (A^T A)^{-1} A^T g_{raw}$$

The same approach is used to find either the drift or scale factor if the other one is given.

The gravity residuals prior to low-pass filtering are shown in Figure 68.

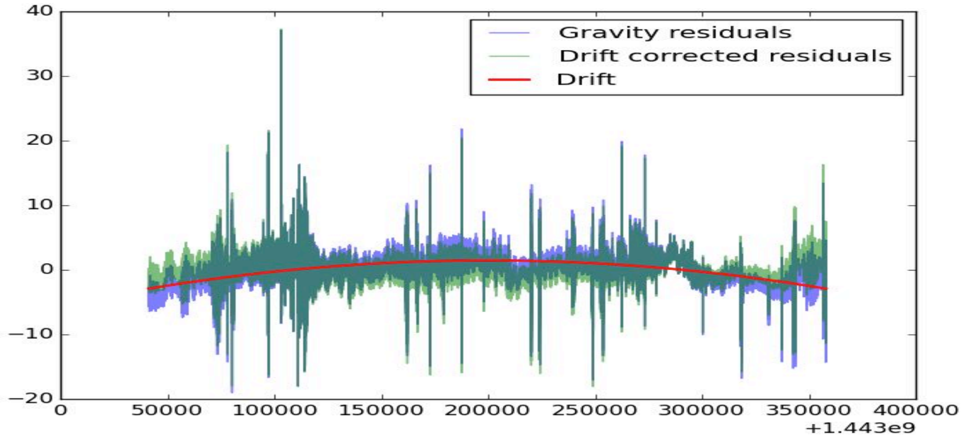

Figure 68: Lacoste/Scripps gravity residuals after first and second order drift correction. Y-axis is in µGal.

After all the corrections have been subtracted from the raw data, a low-pass filtering is performed on the residuals using a Kaiser filter with a shape-parameter of 10 and filter lengths between 1000 and 3600 seconds. Low-pass filtered residuals are shown in Figure 69.

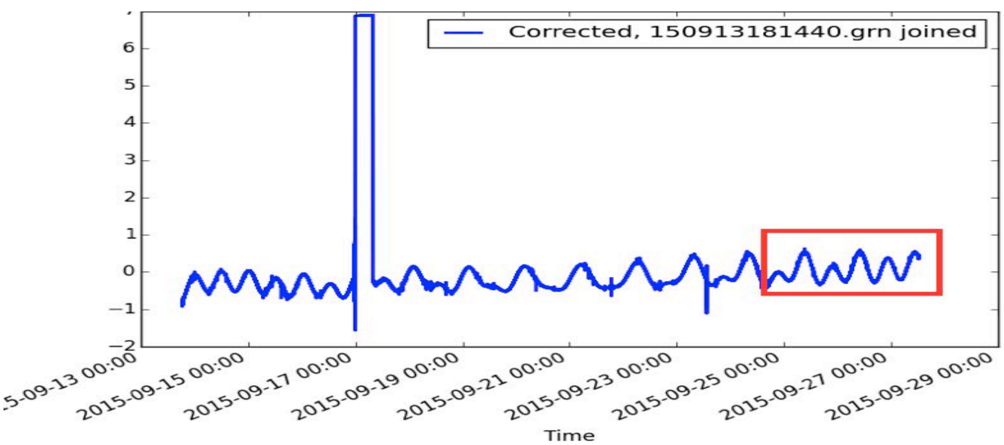

Figure 69: LaCoste/Scripps gravity residuals after drift and tide corrections and low-pass filtering. Y-axis scale is in µGal. The part selected for temperature correlation is marked by the red box.

8.1 Temperature and drift corrections of Lacoste/Scripps gravity data

A diurnal periodicity of the residuals can be seen in Figure 69. To investigate if some of this is caused by day-night temperature fluctuations, we cross-plotted the temperature recorded adjacent to the gravimeter and the gravity residuals, shown in Figure 70. We selected the time interval with the most stable residuals, presumably the least affected by other sources (e.g. remaining drift), for the temperature-gravity cross-plot in Figure 70. This is shown as a red rectangle in Figure 69. The temperature was sampled at 60 s, and a piecewise linear interpolation was performed to get the same sample period of 1 s as for the gravity data. Day-night temperature variations were up to 1°C. The linear trend line has a gradient of 2.2 µGal/K. This gradient was used to calculate the temperature correction for all the LaCoste/Scripps data.

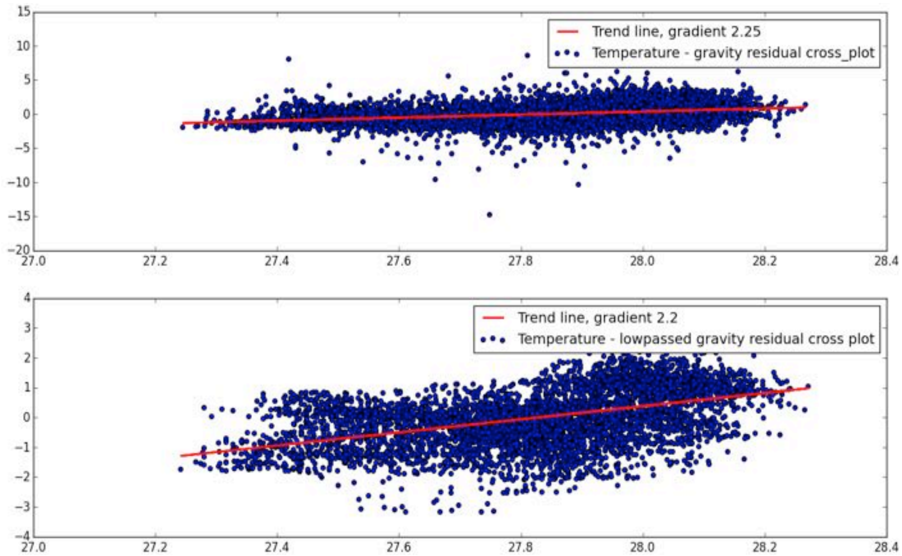

Figure 70: Cross plot of low-pass filtered gravity residuals (in µGal along the y-axis) and temperature (in °C along the x-axis). The best-fit linear trend has been added in red.

The gravity correction is calculated as follows,

$$g_{temp_{correction}} = (T - \bar{T})C_t$$

where $\bar{T}$ is the average temperature and C_t the temperature-gravity gradient.

The final low-pass filtered gravity residuals after temperature, solid earth tide, ocean loading and drift corrections is shown in Figure 71, from the 18th to the 27th of September. There is an about 12-hour period signal, which could be caused by residual tides. The gravity change calculated from air pressure, shown in red, have similarities with the gravity residual, but is shifted about 1 day. However, if an air pressure correction is applied to the gravity data, we get higher residuals related to long-period drift.

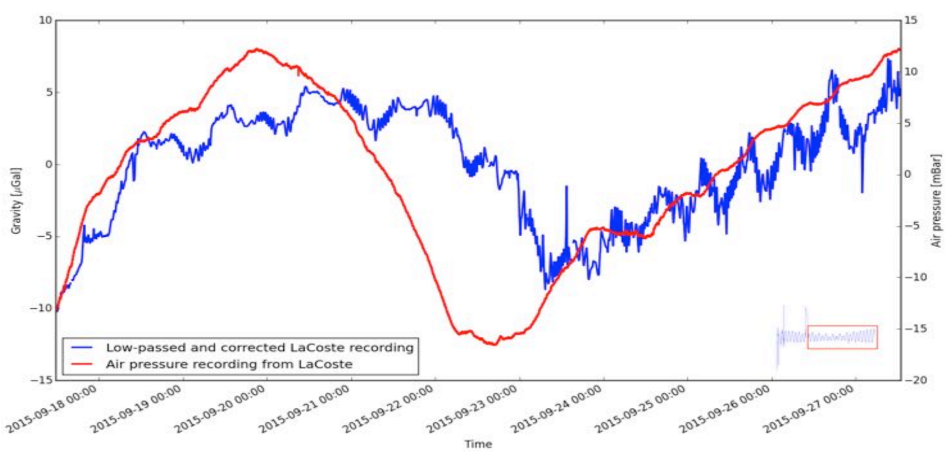

Figure 71: The gravity residuals (blue line) and air pressure (red line) recordings from the LaCoste/Scripps gravimeter. The residual is corrected for ocean loading, solid earth tide, and a second order drift. This is the part of the full record marked by a red square in the thumbnail in the lower right corner.

To investigate the origin of the residual pattern further, we applied a linear drift correction only, shown as the blue curve in Figure 72. We observe a strong second order drift in the residuals, fitted by the red curve to get the green curve; the 2nd order drift correction. The large difference in residuals between 1st and 2nd order corrections show how sensitive the result is to the drift correction. The data have not allowed further conclusions.

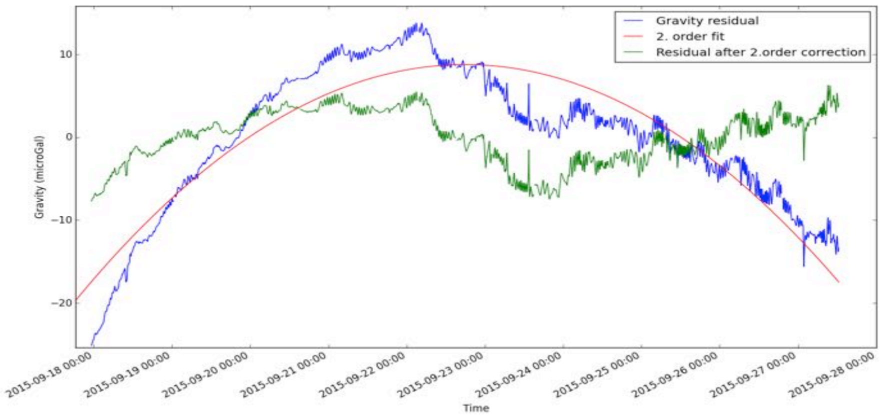

Figure 72: Low-pass filtered gravity residuals after 1. order (blue) and 2. order (green) drift corrections. Filter length was 1800 seconds.

8.2 gPhoneX

The air pressure and level (tilt) corrections applied to the gPhone data are shown in Figure 73. These are provided by the gPhone software. Low-pass filtered gravity residuals after September 18th are shown in Figure 74, with and without air pressure correction. We observe that the air pressure corrected residuals are smaller. The non-linear drift before the 18th of September disguises the effect of the air pressure correction. Drift correction has been applied to the data.

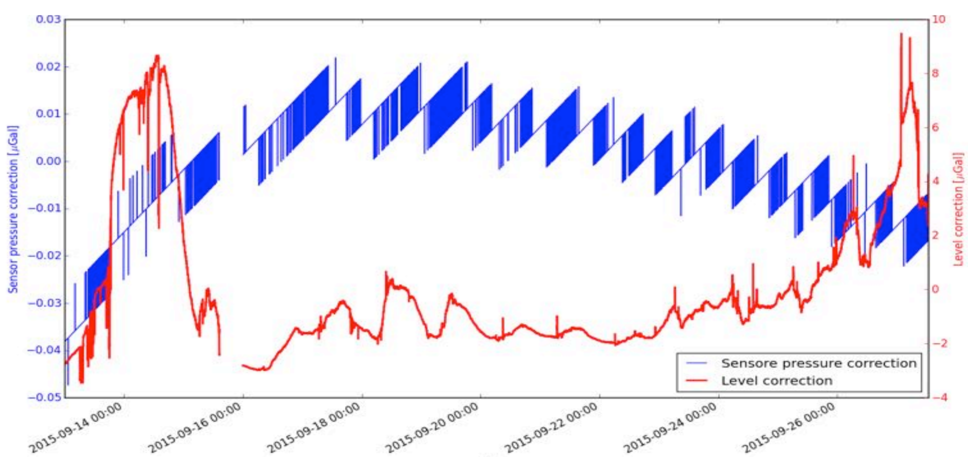

Figure 73: The inherent and applied corrections for the gPhoneX data. Note the different scales for the different corrections.

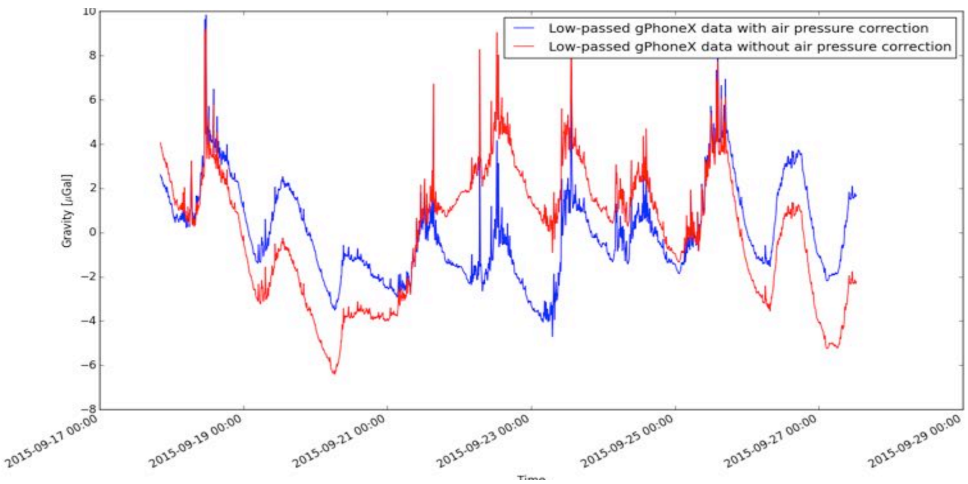

Figure 74: Low-pass filtered gravity residuals from the gPhoneX gravimeter, with and without air pressure correction (blue and red curves, respectively).

8.3 Temperature correction of gPhoneX data

A temperature correction was investigated and applied, using the sensor temperature data. Figure 75 show the correlation between the gravity residuals and the sensor temperature. The residuals are calculated by subtracting the correction from air pressure, solid earth tide, ocean loading and drift. The red line is the linear fit.

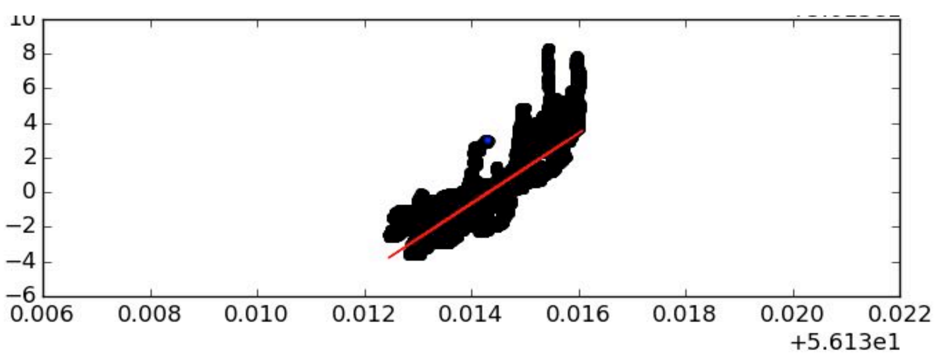

Figure 75: Temperature and gravity residual cross plot, and corresponding trend line. The x-axis is sensor temperature in °C, and the y-axis is gravity residual in μGal. Gravity residuals have been low-pass filtered.

This gives us a correlation coefficient $C_T \approx 2000 \frac{\mu Gal}{C^\circ}$. The temperature correction is then calculated as:

$$g^T_{correction} = C_T(T_S - \bar{T}_s)$$

8.4 Spike evaluation of gPhoneX data

Positive "spikes" or short periods of high amplitude pollute the low-pass filtered gPhoneX gravity residuals, as seen in the period from the 22nd to the 25th of September shown in Figure 76. Close-ups of four spikes reveal a more complex origin than single incorrect data points, shown in Figure 77.

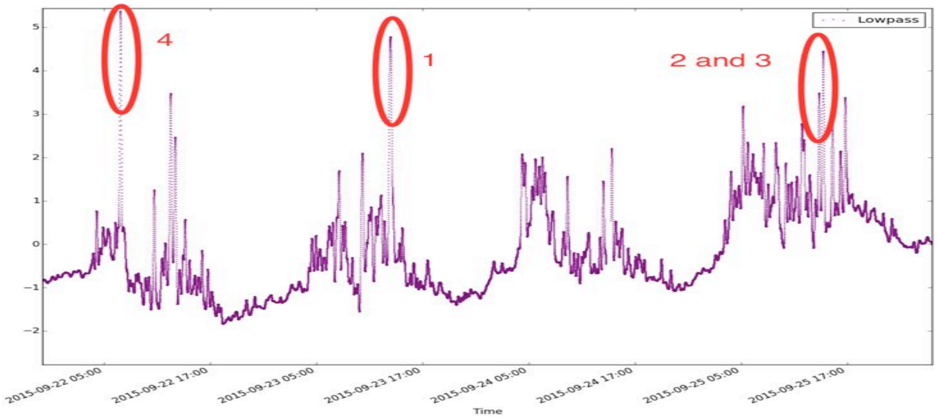

Figure 76: Low-pass filtered gPhone gravity residuals from September 22nd to 25th. Four spikes that have been further investigated are marked with red ovals.

Noise event #1 looks like an obvious spike, but there is at least three samples contributing to this event (Figure 77). The spike in the low-pass filtered data was found at September 23, at 13:24, but is probably caused by the event seen in the close-up at 13:25.

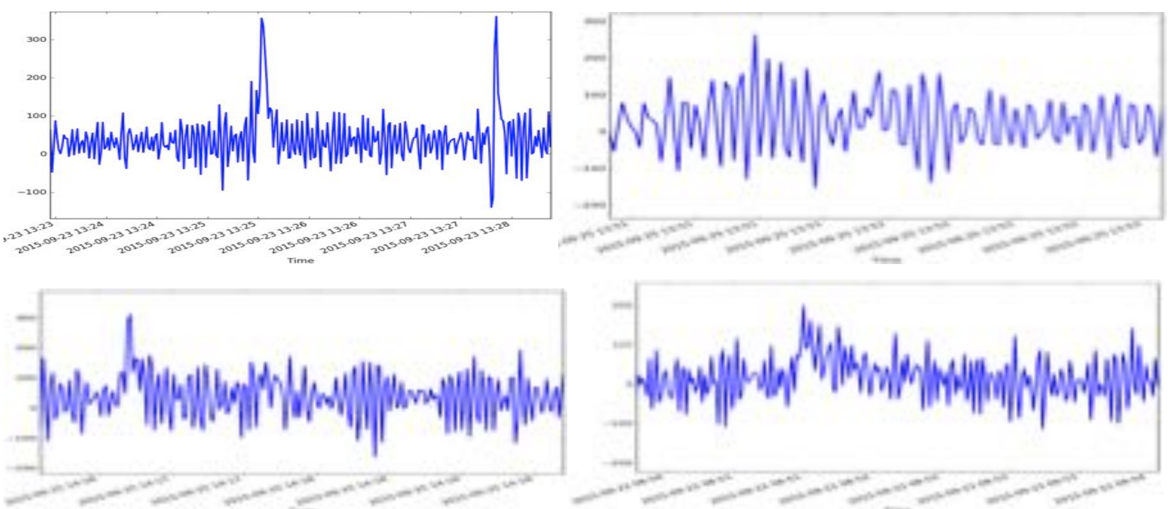

Figure 77: Raw data close-up of 5 minutes around of noise events. Upper left: First event identified at 13:24 in the low-pass filtered data. Upper right: second event. Lower left: Third event. Lower right: Fourth event.

The second and third noise events marked in Figure 76, at 13:52 and 14:18 at September 25th, show no spike in the close-ups (Figure 77). A large spike was found in the low-passed residuals at 13:52, but there is no visible spike in the raw data. For the third noise event, there is no spike in the raw data at 14:18. However a large spike is seen at 14:16, and this may be the cause. The fourth noise event marked in Figure 76, at September 22nd 6:52, corresponds with a low-frequent shift in the gravity residuals. We observe a shift in the gravity residuals at 06:51, probably causing the spike found in the low-passed data at 06:52.

We conclude that the “spikes” are caused by real earth movements. It could be persons walking nearby, or heavy traffic on the road up to 75 m away.

8.5 Solid Earth Tide model time shift and gPhone data.

The low-pass filtered gravity residuals are plotted in Figure 78, together with the solid earth tide and ocean loading corrections (red clipped line). The residuals peak at a few μGal, with periodicity of about 24 hours. All peaks in the gravity residuals occur near the (positive) zero crossing of the earth tides. This could indicate that there is a time offset between the solid earth tide model and the true gravity tides.

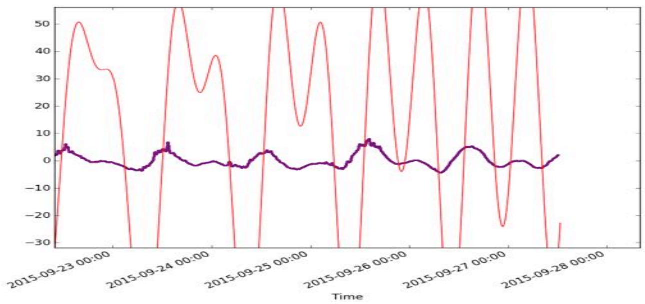

Figure 78: Low-pass filtered gravity residuals (purple) and the solid earth tide correction (red), from 23rd to 28th of September. Y-axis is in μGal.

To further investigate this, we calculated the RMS error of the difference between the gravity residuals without the solid earth tide and ocean loading correction and these models, for various time-shifts of the model. The result was a curve with a parabolic shape, indicating a minimum at a time shift of approximately 265 seconds, Figure 79. The optimal time shift varied between -135 and -300 seconds dependent of the length of the section of the gravity data used for the calculation. The RMS error was reduced with approximately 0.4 μGal. However, it may be necessary to investigate a much longer time period to make valid conclusions regarding the solid earth tide model. The residuals without and with time-shifts are plotted in Figure 80 together with the solid earth tide model and the gravity data.

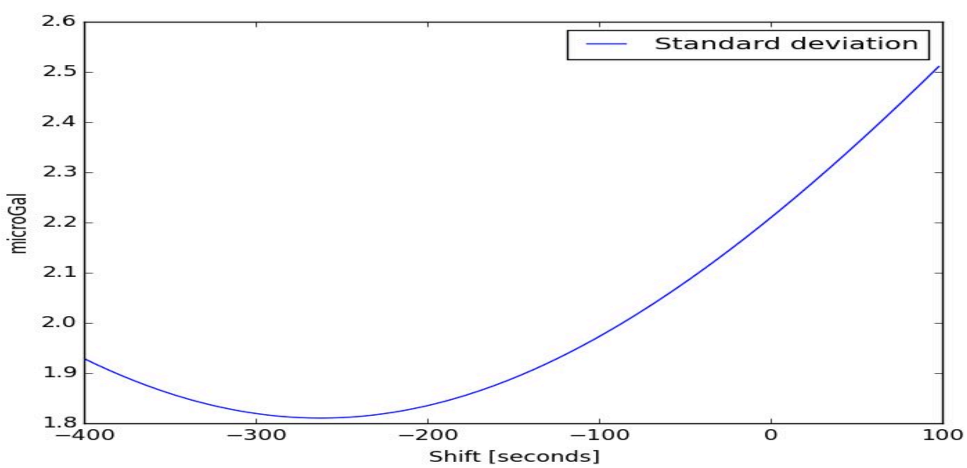

Figure 79: RMS error of the difference between the solid earth tide and ocean loading model and the low-pass filtered gravity data without these corrections, for various time-shifts of the model.

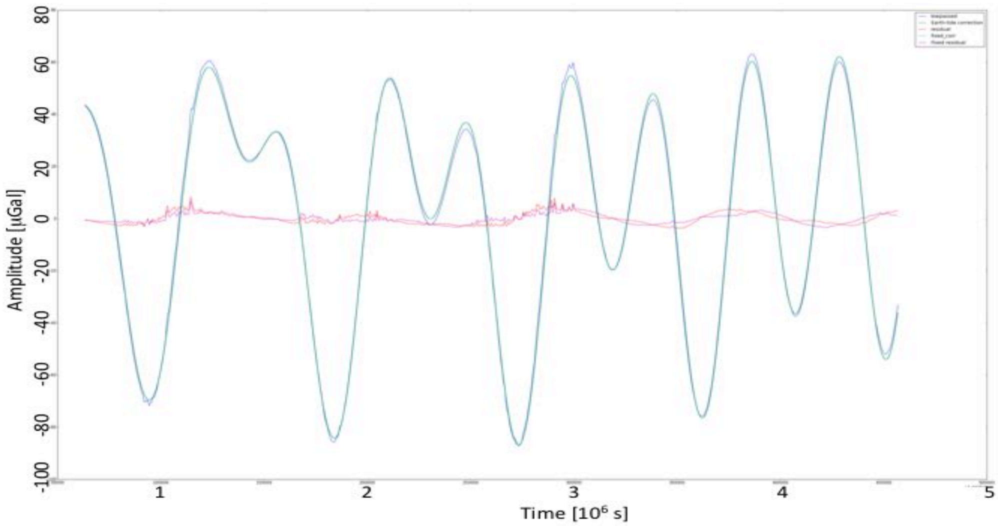

Figure 80: The low-pass filtered gravity signal (blue), the original and time-shifted earth-tide model (green and light blue on top of each other) and the residual before (red) and after (purple) the time shift of the solid earth tide model.

8.6 Comparison of the Lacoste/Scripps and gPhoneX data

Because of the larger uncertainties in the Lacoste/Scripps data, with several noise event the first days, only the last part (from the 23rd to 28th of September) of the recordings were used for comparing the Lacoste/Scripps and gPhoneX data. The residuals are shown in Figure 81, and we observe some correlation between the two curves the last 2-3 days. Gravity residuals from the two meters are cross-plotted in Figure 82, left part. No strong correlation is seen. The correlation coefficients for different time-lags, shown in Figure 82, show an about 12 hour period in the correlation coefficient. This suggests the residuals are related to tidal noise; errors in the solid earth or ocean loading models.

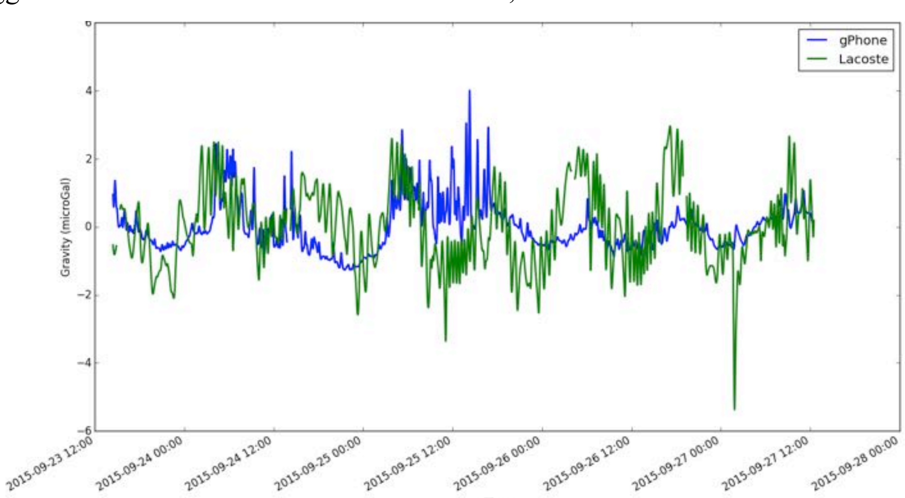

Figure 81: gPhone (blue) and Lacoste (green) gravity residuals for the last part of the survey

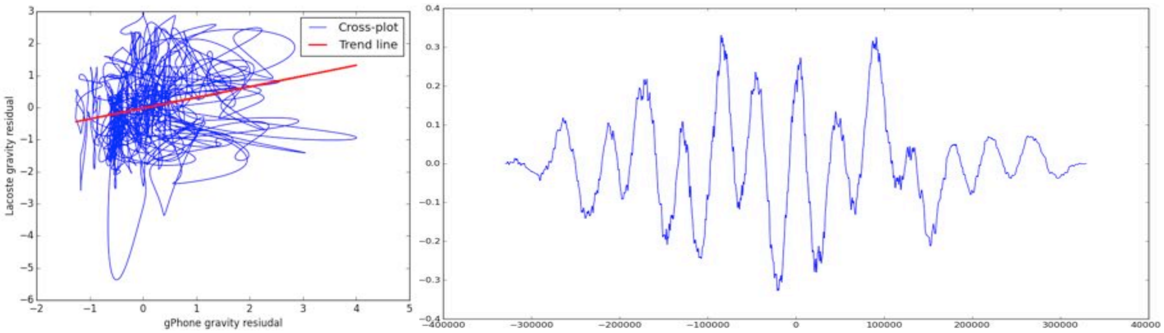

Figure 82: Left: Cross plot of gPhoneX and Lacose gravity residuals. Right: Correlation between gPhone and Lacoste residuals for different time lags. X-axis is time lag in seconds.

In conclusion, the reference gravity data recorded during the 2015 survey show that the earth tide model is good to at least 1 μGal. Longer time series without interruption would be required to resolve smaller deviations.

8.7 Earthquakes

No local earthquakes were recorded in the survey period, but three in the days preceding the main survey (http://www.knmi.nl/nederland-nu/seismologie/aardbevingen):

- 9. September 20:01:51 epicenter Harkstede, Magnitude 1.2, depth 3 km
- 10. September 16:08:08 epicenter Garsthuizen, Magnitude 0.8, depth 3 km
- 12. September 18:16:25 epicenter Sterkrade, Magnitude 2.4, depth 1 km

None of these occurred at the time of gravity measurements.

A teleseismic earthquake of magnitude 8.3 occurred in Chile on the 16th of September 22:54 UTC and was felt in a number of subsequent measurements. This Earthquake was clearly visible in the records of the seismographs at station De Bilt, operated by KNMI.

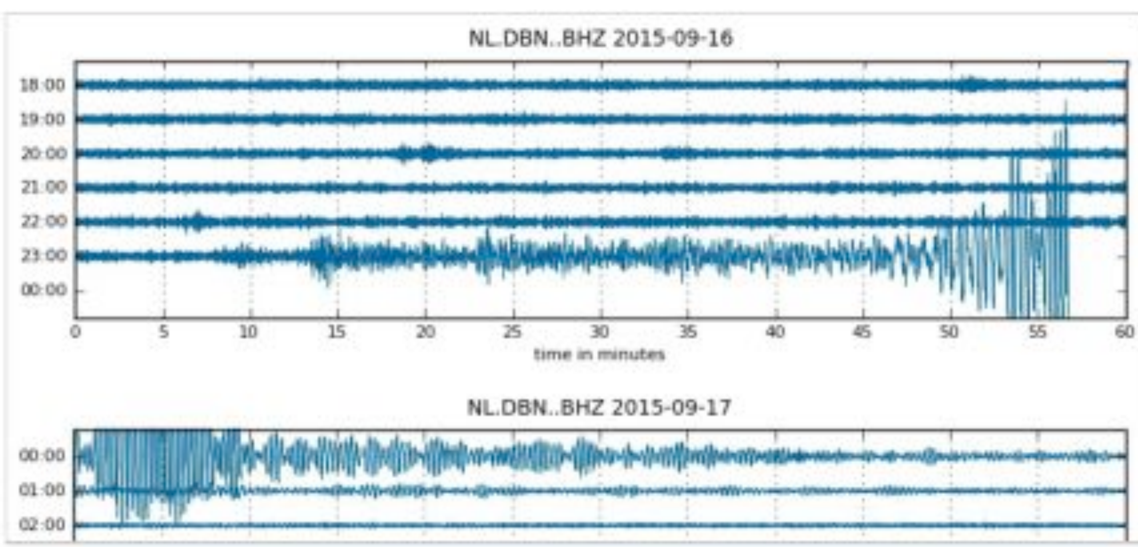

Figure 83: The seismograph of the 16th of September Chile earthquake recorded at the KNMI seismic station De Bilt.

The earthquake was also clearly visible in the records from the gPhoneX gravity meters, see Figure 66. A close-up of about 5 hours at the earthquake (Figure 84) reveals two periods of high amplitudes, with a duration of about half an hour. The peak of the left spike occurs September 16th at 23:56 UTC. This is approximately one hour after the earthquake occurred. The earthquake disturbed about three hours of the recording.

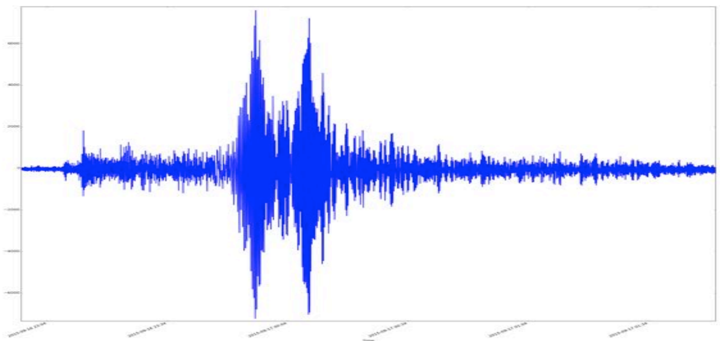

Figure 84: A close-up of the raw-data from the gPhoneX gravimeter at the time of the earthquake in Chile.

9 Scale factor calibrations

The Groningen network has a gravity range of 42.5 mGal when including #33 Assen and #2/#35 Gasselte reference stations, and 33.3 mGal without those two stations. The scale factors then need to be determined within 10^{-4} to have all scale factor errors below 3-4 µGal anywhere within the network. Surveys of absolute calibration ranges were in 2015 done in San Diego prior to shipping the instruments to the Netherlands, and between #402 Westerbork and Monschau in SW Germany just before the survey. Measurements between #2 Gasselte, #29 Zwolle and #23 Maastricht after the main survey were done to provide a relative scale factor calibration between the 1984 and 2015 surveys.

9.1 San Diego calibration March 2015

Coordinates and absolute gravity values for the two stations of the San Diego calibration line in California, CEL (Scripps Range) and MPK (Monument Peak) are shown in Table 18. An observation height of 25 cm above the ground is used for the CG5 sensors. Gravity difference is 405 251.0 µGal. A survey with 3 visits at the top station and 4 at the bottom station was carried out March 12th 2015, from 07:20 a.m. to 8:17 p.m. local time (Table 19), using units #10, 11, 12 and 13. Observers were Joel White and Michael Davis. Weather was reported as "sunny, moderate breeze".

Station	Longitude	Latitude	Gravity at 100 cm above ground [µGal]	Vertical gravity gradient [µGal/cm]	Gravity at 25 cm above ground (sensor height) [µGal]
CEL	242.899611 (-117.100389)	32.892932	979 504 624.2	3.25	979 504 868.0
MPK	243.580 (-116.42)	32.890	979 099 318.5	3.98	979 099 617.0

Table 18: Coordinates and gravity value for the two sites of the San Diego calibration range.

Acquisition measurement #	QuadPro measurement #	Station	Start (UTC)	End (UTC)	Duration [min]
1	0	CEL	14:36	15:10	34
2	2	MPK	16:59	17:21	22
3	3	CEL	19:03	19:24	21
4	4	MPK	20:53	21:15	22
5	5	CEL	22:41	23:01	20
6	6	MPK	01:27	01:51	24
7	7	CEL	03:17	03:38	21

Table 19: List of measurements and times.

Measurement number	Standard deviation of low-pass filtered time series				Linear recovery [nGal/s]			
	U10	U11	U12	U13	U10	U11	U12	U13
0	0.8	0.7	0.5	2.1	1.6	0.6	0.4	-1.8
2	1.0	1.2	2.1	5.1	2.5	3.0	6.4	12.7
3	0.6	0.8	0.6	1.0	-0.1	1.7	1.5	-0.9
4	2.0	3.8	2.7	2.2	5.8	11.6	7.7	4.2
5	0.9	1.3	1.2	0.9	0.5	3.8	3.3	-2.5
6	3.1	7.3	4.9	0.5	8.7	20.6	14.0	0.8
7	0.8	3.9	3.4	0.8	0.4	12.2	10.5	-0.9

Table 20: Standard deviation of low pass filtered time series (column 2-5) in µGal and recovery coefficient (column 6-9) in nGal/s.

The first record for unit 10 had faulty time stamps after a few minutes, and the recording was terminated. A new file started 9 minutes later and has been used in the subsequent processing. The first record for unit 13 had a spiky period, which was taken out, leaving a gap in the time series. The first couple of seconds were removed from the first measurement for units 11, 12 and 13. Measurement #3, unit 13 had the last part of the record removed. Measurement #6, unit 13, got a small portion of the time series removed due to errors in the CG5 temperature reading. Standard deviation and recovery of the low pass filtered time series are shown in Table 20. Six out of 28 records have significantly higher recovery than the others, and are marked in yellow or blue (highest recovery) in Table 20.

The data have been fitted with one linear drift correction, individual for each unit. Deviations from station means are shown in Figure 85. Repeatability results (standard deviations) are shown in the middle column of Table 21. All units have standard deviations below 5 µGal.

Repeatability is better for unit 11 and 12 when leaving out the records with highest recovery – those marked in yellow and blue in Table 20. Numbers are down from 3.1 and 5.3 µGal to 0.5 and 3.0 µGal (Table 21). Leaving out these records did not change the station values / scale factors of any significance.

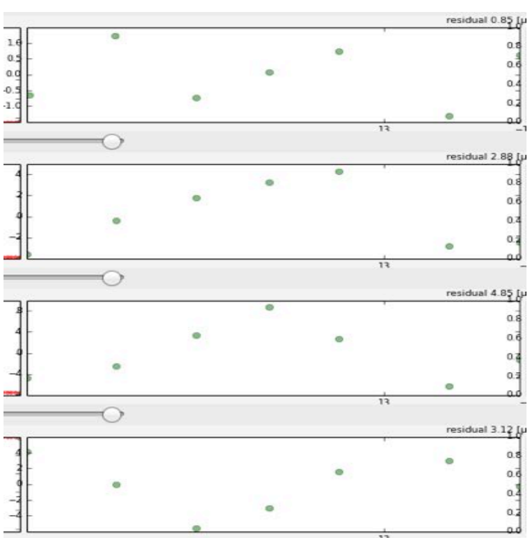

Figure 85: Deviations from station means after a linear drift correction of the units 10, 11, 12 and 13 (top to bottom), independently.

	Repeatability after linear drift correction [µGal]	Repeatability after linear drift correction and omitting records with large recovery [µGal]	Uncertainty in station difference [µGal]
Unit 10	0.9	0.9	0.7
Unit 11	2.9	0.4	0.9
Unit 12	4.9	2.6	3.7
Unit 13	3.1	3.4	2.9

Table 21: Standard deviation of residuals after drift corrections (in µGal).

Scale factors for the various units are listed in the first data line of Table 22. Other calibrations, discussed lager in the report, are included in the same Table. Uncertainties can be calculated from repeatabilities of the relative measurements and absolute station uncertainties, combined. Uncertainties in station differences are listed in the rightmost column in Table 22. The absolute gravity difference at the San Diego range may have an uncertainty (standard deviation) of about 2 µGal. This transforms into uncertainties of 5-10 × 10^{-6} in the scale factors, or 0.04-0.08 in the scale factor numbers given in Table 22.

	U10	Uncertainty	U11	Uncertainty	U12	Uncertainty	U13	Uncertainty
San Diego March 2015	8661.03	0.04	8087.22	0.04	8091.54	0.08	8595.66	0.07
Monschau September 2015	8663.139	0.16	8090.119	0.16	8092.861	0.16	8592.185	0.16
Relative scale factor between units using all survey measurements (relative to U10)	0		0.06		0.27		0.25	
Tie of survey data to #402 Westerbork and #401 Aurich	8665.998		8092.789		8095.531		8595.020	
2015 fast track	8661.31		8088.396		8091.153		8590.397	
2015 final processing	8663.139	2.9	8090.119	2.7	8092.861	2.7	8592.185	2.9

Table 22: Scale factors calculated from various calibrations.

9.2 Westerbork - Monschau calibration September 2015

Another calibration survey was done September 6th 2015, with measurements in #402 Westerbork, Monschau and again #402 Westerbork. This gives a gravity range of 303 532.1 µGal at 25 cm height (Table 24). The drive between the stations take about 4 hours, and the three measurements can be done within a 12 hours working day. This range seemed the most attractive compared to alternative absolute calibration sites listed in Table 23.

	Range [mGal]	Distance [km]	Driving time [hr]	Driving time to first site [hr]
Westerbork – Monschau (SW Germany)	304	349	3.9	-
Aurich – Torfhaus (Harz, Germany)	277	340	3.9	-
Braunschweig – Torfhaus (Harz, Germany)	171	57	0.8	3.7
Aarhus (Denmark) – Torfhaus (Harz, Germany)	542	586	6.2	4.4
Jongfrau calibration range (Switzerland)	479			9.7

Table 23: Five alternative gravity ranges, with distances and travel times.

Site	Description	Latitude	Longitude	Height [m]	Gravity at floor [µGal]	Uncertainty [µGal]	Vertical gravity gradient [µGal/cm]	Gravity at 25 cm above ground [µGal]
Westerbork	Bunker	52.9148	6.6038	15.8	981 309 070.1	+/- 1.0	-2.926	981 308 997.0
Monschau	Basement	50.55725	6.2355	516.7	981 005 540.9	+/- 1.9	-3.04	981 005 464.9

Table 24: Coordinates and gravity value for the two sites of the Monschau calibration range.

The Monschau St. Michael Gymnasium www.mgm-monschau.de, has phone +49 2472 800100 and Address Walter-Scheibler-Str. 51, D-52156 Monschau. The local contact person is Dr. Marc Henning Zoeller (email: marc.henning.zoeller@gmail.com, phone +49 175 568 46 44). He was helpful and forthcoming during Quad's visit September 6th. Another contact person is Marie Luise Boden (email: info@mgm-monschau.de).

Absolute gravity at the Monschau site has been measured by the Royal Observatory of Belgium in Brussels at spring and fall times from May 2000 to September 2014 (Figure 86, left side). From Michel Van Camp we have received the values listed in Table 24 (in e-mail of September 21st 2015). These were obtained for the average of 15 sets of fall values. The time-lapse rate of change has not been significantly different from zero.

Figure 86: The basement of the St.-Michael Gymnasium in Monschau, Germany, with absolute measurement (left) and relative measurement (right).

Mark Zumberge and Joel White carried out the relative measurements with all four gravimeters. The crew departed with the survey car from Ten Boer 9:15 (local time) and came back 22:30. Each measurement lasted 20 minutes. QC plots of the three measurements are shown in Figure 87 - Figure 89. Time series are stable, with recovery less than +/-11 nGal/s. While the raw sample RMS was 230-400 µGal at Westerbork, it was as low as 23-28 µGal at the more inland site of Monschau.

Site	Start of measurement (UTC)	Sample standard deviation [µGal]	Standard deviation after low-pass filtering [µGal]
Westerbork	08:44	360	2.4
Monschau	14:32	25	2.2
Westerbork	19:20	265	1.5

Table 25: Key data for the measurements of the calibration survey to Monschau.

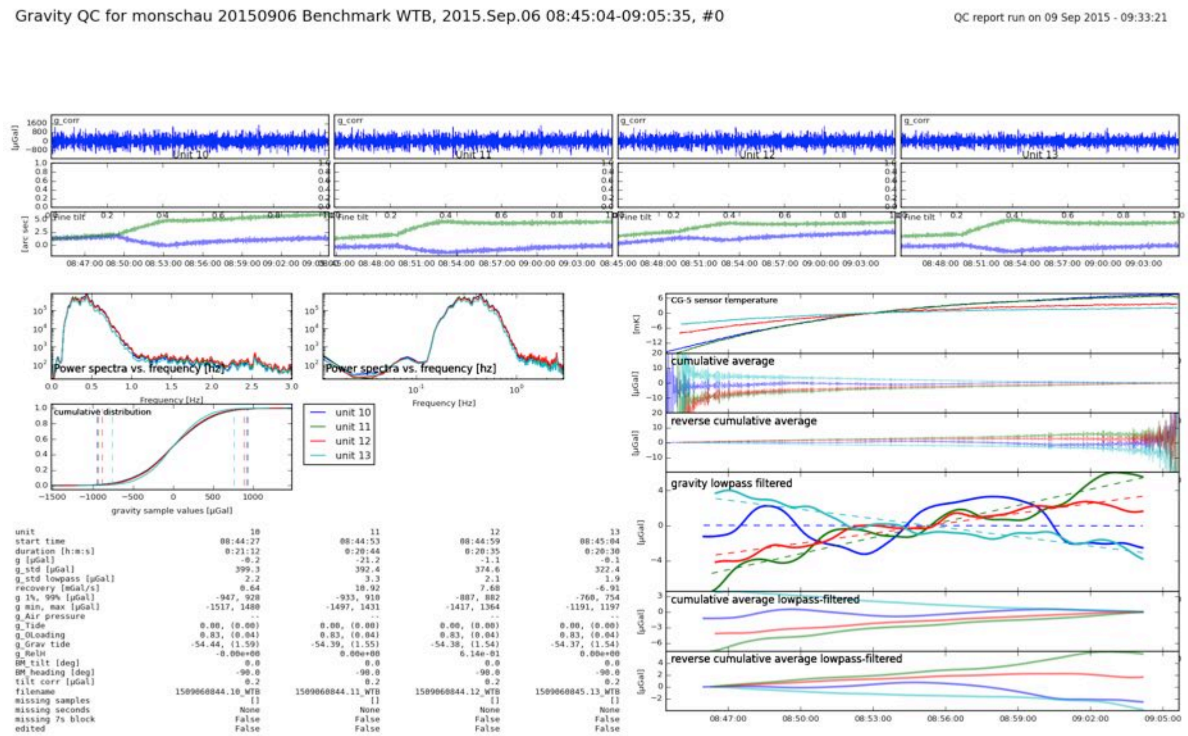

Figure 87: QC plot of first Westerbork measurement.

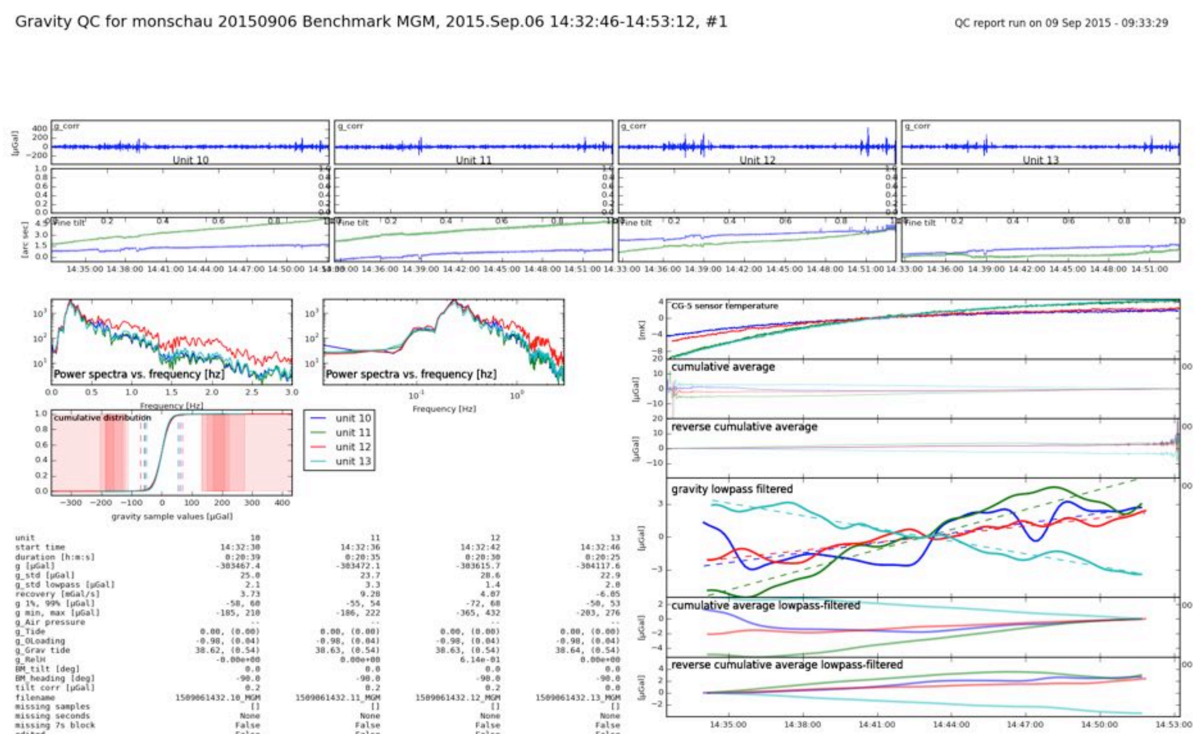

Figure 88: QC plot of Monschau measurement.

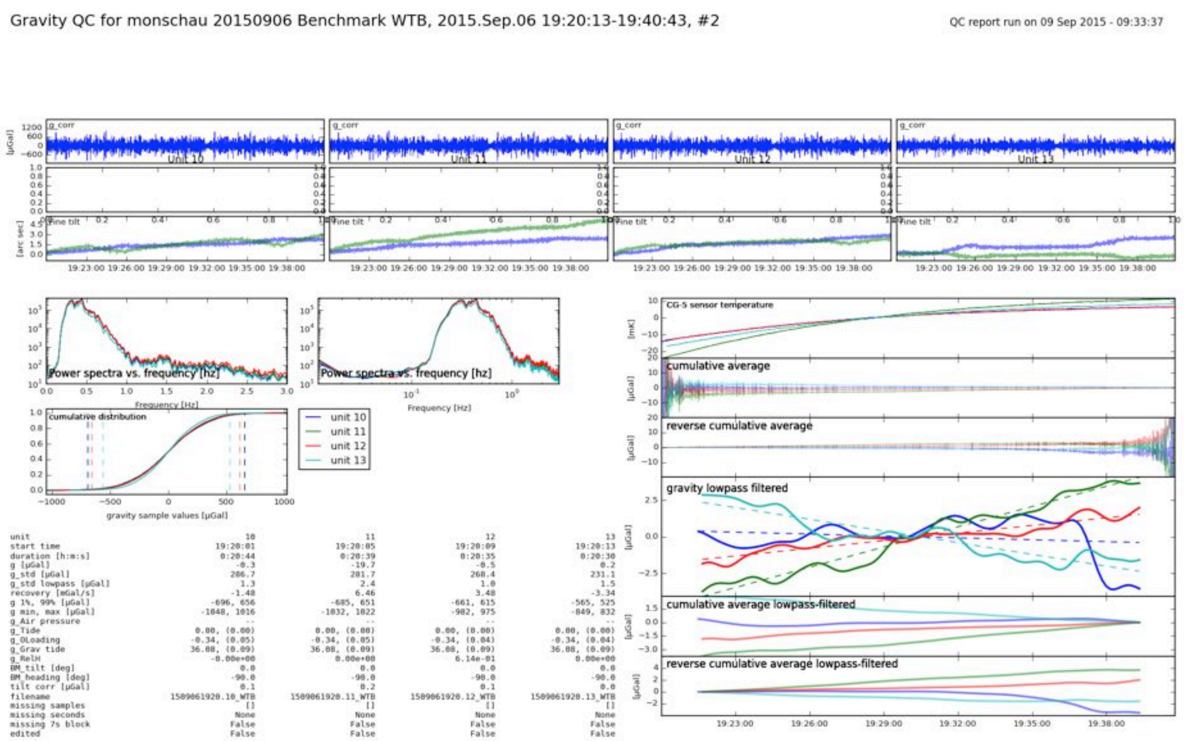

Figure 89: QC plot of last Westerbork measurement.

Measurement number	Standard deviation of low-pass filtered time series [µGal]				Linear recovery [nGal/s]			
	U10	U11	U12	U13	U10	U11	U12	U13
0	2.2	3.3	2.1	1.9	0.6	10.9	7.7	-6.9
1	2.1	3.3	1.4	2.0	3.7	9.3	4.1	-6.1
2	1.3	2.4	1.0	1.5	-1.5	6.5	3.5	-3.3

Table 26: Standard deviation of low pass filtered time series (column 2-5) in µGal and recovery coefficient (column 6-9) in nGal/s.

Resulting scale factors are shown in Table 22. Deviations from the preceding San Diego calibration is significant for all units. Uncertainties in the range measured by the Scintrex gravimeters are not straightforward to assess, because of the perfect linear drift fit to the two measurements at Westerbork. A somewhat conservative estimate may be a 6 µGal uncertainty in the Westerbork – Monschau difference, transforming to +/- 2 × 10^{-5} in the scale factors, or +/- 0.16 in the scale factor numbers given in Table 22. Absolute station uncertainties of 1.0 and 1.9 µGal (Table 24) are insignificant in this calculation

9.3 Gasselte – Zwolle – Maastricht calibration September 2015

Site #23 Maastricht was measured as part of the 1984 survey, and site #29 Zwolle was measured as part of the 1984 and 1988 surveys. Both are inside railway station buildings, and photographs of the sites became available during the 2015 survey (Figure 90). By measuring differences between these and #2 Gasselte in 2015, scale factors applied to the past surveys can potentially be adjusted.

Figure 90: Photos from the Maastricht (above) and Zwolle (below) gravity sites at the railway stations. The measurements in 1999 are shown to the left, and the sites in 2015 to the right.

Access to #23 Maastricht, in the main hall of the station building, is closed between 1:30 and 5:00 on workdays, and until 6:00 or 7:00 on weekends. The station manager in 2015 was Ben Schols (+31 6 194 622 89). Wim van Der Veen of NAM provided Quad an access grant before the measurement. The building is busy during daytime, and an evening or early night measurement is preferred for lower noise conditions.

Access to #29 Zwolle is closed between 1:00 and 5:30 on workdays and until 6:30 on weekends. Station manager in 2015 was Jan Hartman (+31 6 5130 2260). The entrance area is busy during daytime; a measurement was for that reason given up mid-Sunday September 6th.

Joel White and Michael Davis carried out the Gasselte-Zwolle-Maastricht-Gasselte measurements September 29th-30th, using units 10, 12 and 13, and with timing as shown in Table 27. The survey was timed such that the railway station measurements were made in the late evening.

Acquisition measurement #	QuadPro measurement #	Station	Date	Start (UTC)	Duration [min]
1	0	Gasselte church	September 29th	16:38	20
2	1	Zwolle	September 29th	18:10	30
3	2	Maastricht	September 29th	21:30	30
4	3	Gasselte church	September 30th	01:40	25

Table 27: List of measurements and times for the Zwolle and Maastricht measurements.

All measurements show stable time series, with low recovery (Table 28). These calibration data have in QuadPro been defined as a separate survey (2015B) which is related to the surveys in 1984 and 1988 using the time-lapse tool. Table 29 shows the gravity ranges as measured and processed in 2015, the residuals in the 1984-data when comparing to 2015, and the required scale factor adjustment for 1984 data to match 2015.

Measurement number	Standard deviation of low-pass filtered time series [µGal]			Linear recovery [nGal/s]		
	U10	U12	U13	U10	U12	U13
0	1.9	0.7	1.0	-4.0	-0.1	-2.1
1	2.0	2.8	2.8	-2.6	5.7	-5.5
2	1.4	3.1	2.7	-1.4	6.7	-5.4
3	0.5	0.5	2.6	1.1	-0.2	-6.4

Table 28: Standard deviation of low pass filtered time series and recovery coefficient.

Station	Gravity difference [µGal]	Gravity residual [µGal]	Required scale factor adjustment
2 Gasselte church	0	0	
29 Zwolle	24 038.5	7.3	$3.0\ 10^{-4}$
23 Maastricht	187 353.6	43.1	$2.3\ 10^{-4}$

Table 29: Gravity values at the stations in the Gasselte – Maastrich range.

9.4 History of scale factor calibrations

Time series of the scale factors determined from absolute site calibrations since the sensors were first used in 2013 are shown in Figure 91. The numbers in the two uppermost rows of Table 22 correspond to the most recent data points in the plots. Variations from calibration to calibration is of order 1-3 × 10^{-4}. Most of the data points follow a trend; increasing for unit 10 and 11, decreasing for unit 13.

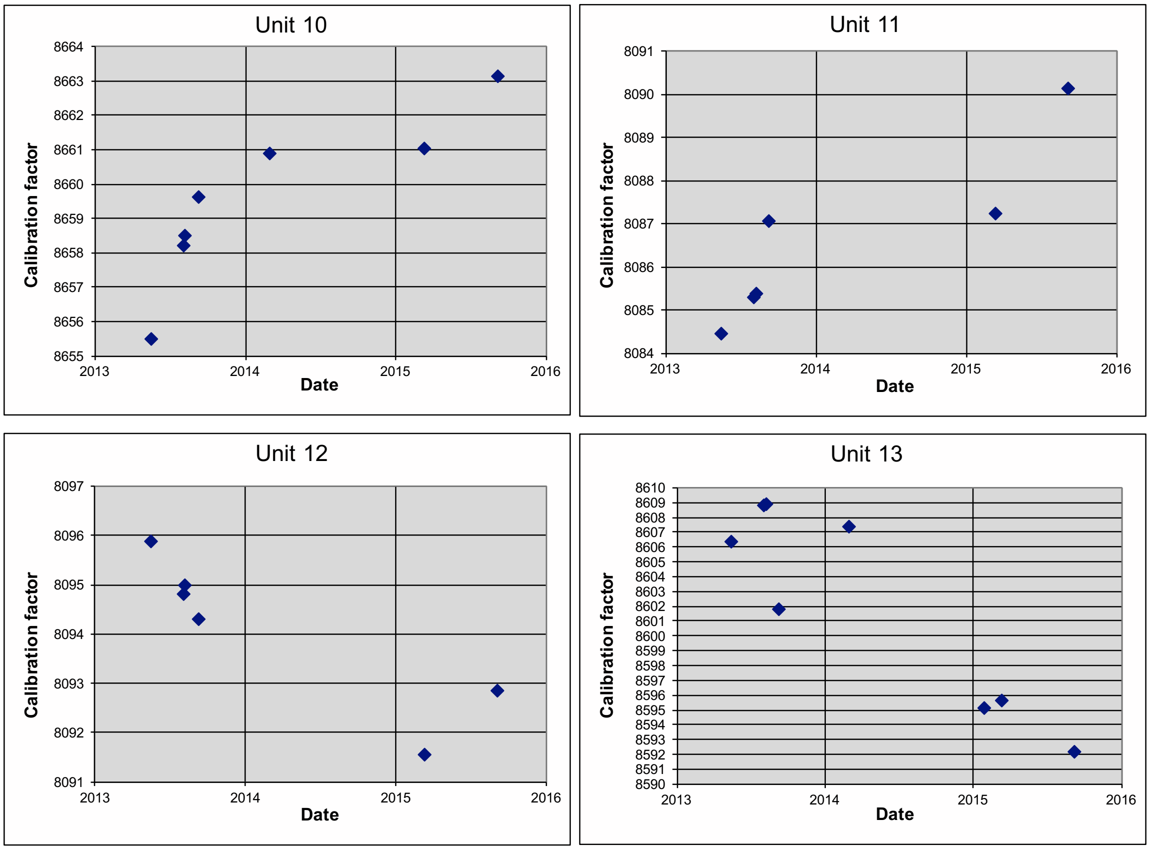

Figure 91: History of scale factor calibrations since 2013.

9.5 Unit differences in 2015 survey

Unit differences are displayed in Figure 92 as a function of gravity (relative to #404 Overschild). Standard deviations of the unit differences are from 3.8 to 5.2 µGal. Trend lines, shown in Figure 92, have slopes corresponding to scale factor values relative to unit 10 as listed in Table 22. The numbers given are terms required to be added to the scale factors (e.g. 0.06 needs to be added to 8090.119 for unit 11, to obtain the scale factor of 1090.179 which gives zero slope in the unit difference vs. gravity best-fit line. The values, up to 0.27, are less than the uncertainty in the scale factors and in determination of the slope fit. A further adjustment of the scale factors based on this has thus not been done.

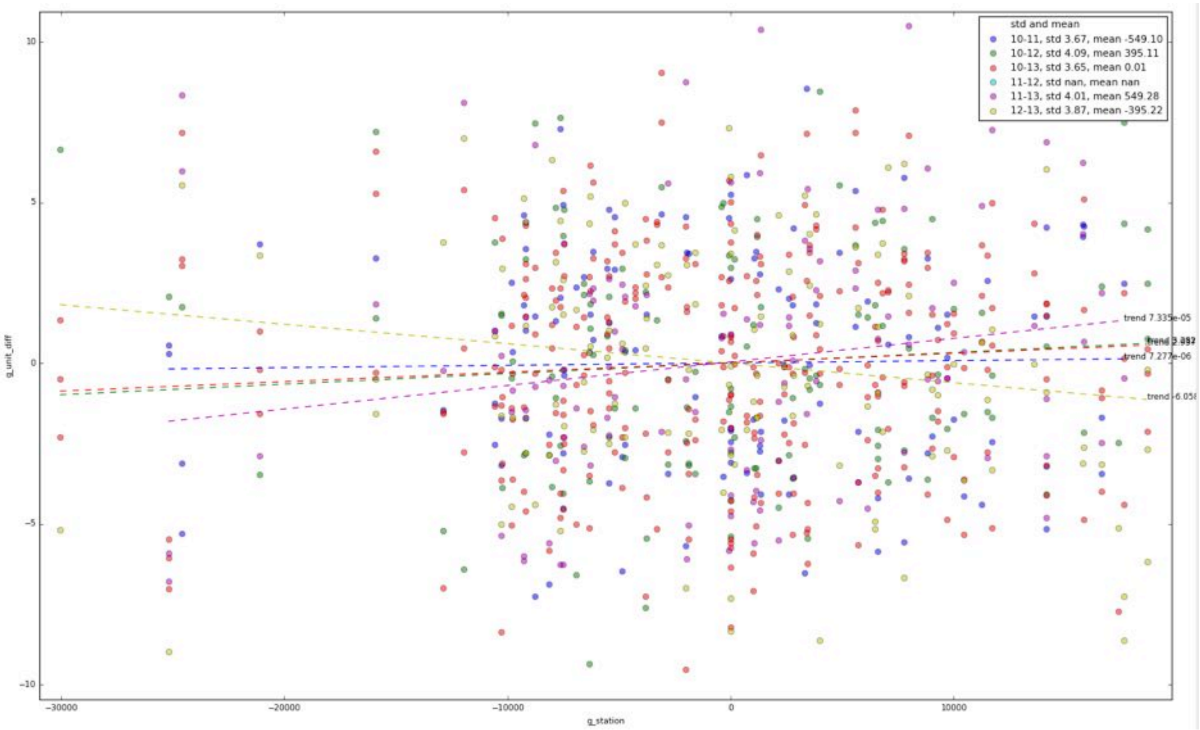

Figure 92: Cross plot of unit difference vs. gravity value relative to station 404.

10 Tilt calibrations

Tilt calibrations took place in the Ten Boer garage September 10th, 12th, 17th and 30th. Only the x-axis was calibrated on the 12th, and only unit 12 on the 17th. Resulting calibration parameters are shown in Table 30. Xnull for U11 and Ynull for U12 both have a change of about 150 from first to last Groningen calibration. The average values (bottom row of Table 30) have been used in the post-processing. These may cause tilts which are up to 4 arcsec off the intended value during aquisition. This is insignificant when recorded tilt is close to zero, but can cause a 1 µGal error for 10 arcsec recorded tilt.

Date	U10				U11				U12				U13			
	Xnull	Xsens	Ynull	Ysens	Xnull	Xsens	Ynull	Ysens	Xnull	Xsens	Ynull	Ysens	Xnull	Xsens	Ynull	Ysens
February 24th	33105	5.14	31524	4.78	32353	5.39	32433	5.34	31799	4.85	32650	5.31	32733	5.28	32598	5.50
September 10th	33332	5.17	31801	4.77	32533	5.44	32515	5.31	31824	4.93	32724	5.35	32525	5.42	32771	5.48
September 12th	33319	5.07			32477	5.41			31818	4.91			32575	5.41		
September 17th									31831	4.89	32891	5.33				
September 30th	33200	5.18	31907	4.79	32394	5.43	32602	5.31	31791	4.90	32874	5.33	32489	5.45	32833	5.48
Survey average	**33260**	**5.17**	**31854**	**4.78**	**32463**	**5.43**	**32558**	**5.31**	**31808**	**4.91**	**32800**	**5.34**	**32507**	**5.43**	**32800**	**5.48**

Table 30: Tilt parameters found in various tilt calibrations in 2015. Xsens and Ysens values shall be multiplied by 10^{-2}. Survey averages, used in the processing, are shown in the bottom row.

11 Absolute gravity ties of the relative network

The network of relative measurements can for 2015 be tied to three absolute stations; at #404 Overschild, #402 Westerbork and #401 Aurich. While the absolute value at the two latter were pre-determined by several measurements showing a stable value over time, the first absolute measurement was done in #402 Overschild during the main survey. This will have to be repeated during or closely timed to a future time-lapse survey.

Figure 93: The Overschild windmill during the absolute gravity measurement.

11.1 The absolute gravity measurement in Overschild windmill

An absolute gravity measurement took place in the "Windlust" windmill, Overschild (Figure 93), from September 16th at 19 UTC to September 17th at 05 UTC. The location also served as a central reference for the relative gravity measurements, receiving 14 visits with CG5's during the 2015 survey. The absolute measurement has been described in a separate report (Reudink and Klees 2015), and is summarized here. TU Delft's Micro-g FG5 #234 made in 2008 was used, and the gradient measurements were done by Scintrex CG5 SN41301, made in 2015.

The top soil layer around Overschild is mainly peat and clay (Figure 94), and the soft ground makes Overschild a noisy environment for gravity measurements. In particular, during periods of strong winds and waves from the North Sea and Atlantic Ocean, the noise level is expected to be significantly higher than on rocky ground.

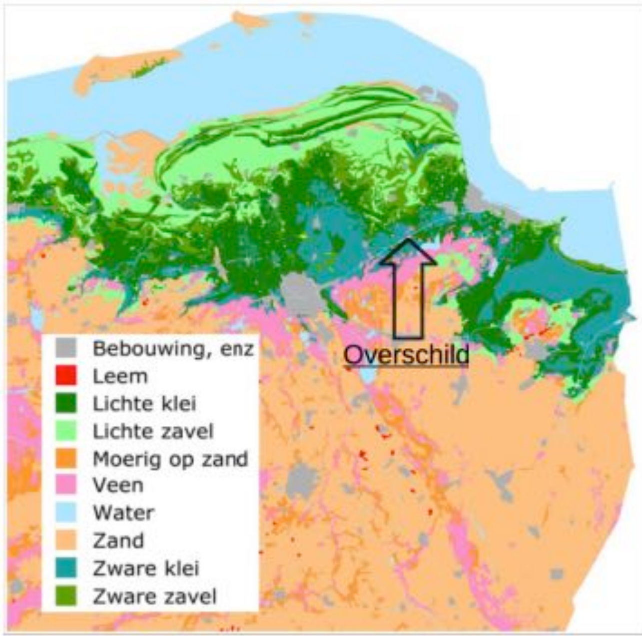

Figure 94: Overschild is located in an area with peat and clay. Gravity measurement noise is expected to be high due to the soft ground.

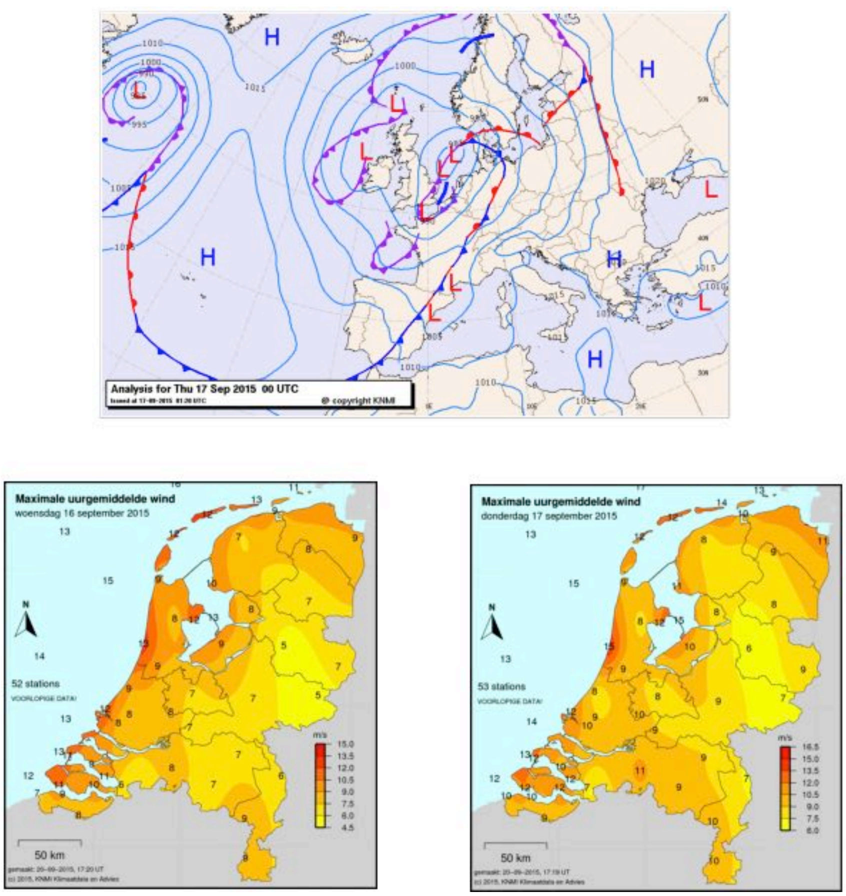

Figure 95: Weather and wind charts over the Netherlands during data acquisition.

During data acquisition, a low pressure system moved North-East over the North Sea, shown in Figure 95. This system produced a moderate wind field over the Netherlands. The Chile earthquake of September 16 (page 73) affected the measurements.

The absolute gravity was recorded by René Reudink, and the recording included 11 sets of 200 drops each. As an example, Figure 96 shows the 200 drops for set #1 and #11, respectively. The drop standard deviations range from 44 µGal to 175 µGal except for sets #6 and #7, with much higher values due to the Chile earthquake (Appendix B, Table 61). These standard deviations are significantly higher than what we obtain under calm conditions on sandy grounds in the Netherlands (±5 to ±25 µGal). This can be explained by the increasing wind during data acquisition in combination with the soft ground. Set number 1, acquired in the early evening of September 16th has the smallest standard deviation of 44 µGal; at that time the wind was rather weak. Results of the sets are shown in Figure 97. The Earthquake is clearly visible in the set series by the unusually large drop scatter of set no 6 (drop SD = 3482 µGal) compared to the other sets, and still above average SD for set no 7. Fortunately, the Chile earthquake had no significant effect on the absolute value of gravity, which is computed as the weighted mean over the sets. When removing set no 6 from the analysis, the mean does not change within uncertainty (Figure 97 vs. Figure 98). The same applies if sets no 6 and 7 are removed from the analysis (Figure 98, right side). It seems as the wave shapes from the long distance Earthquake are well averaged out when computing the mean over all sets.

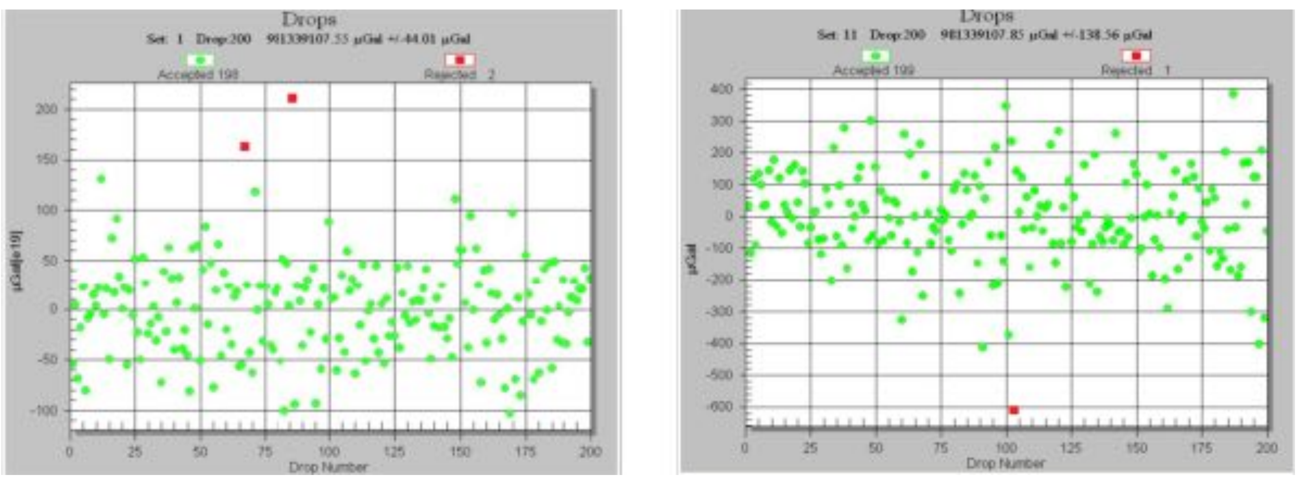

Figure 96: The drop scatter of set no 1 (left) and no 11 (right). The corresponding drop standard deviation (SD) is 44 µGal and 139 µGal, respectively.

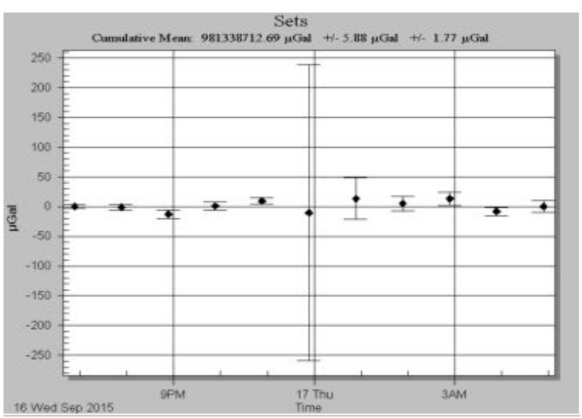

Figure 97: All eleven sets measured at the Overschild station. The error bars indicate the set SD. Absolute gravity refers to 130 cm above floor level.

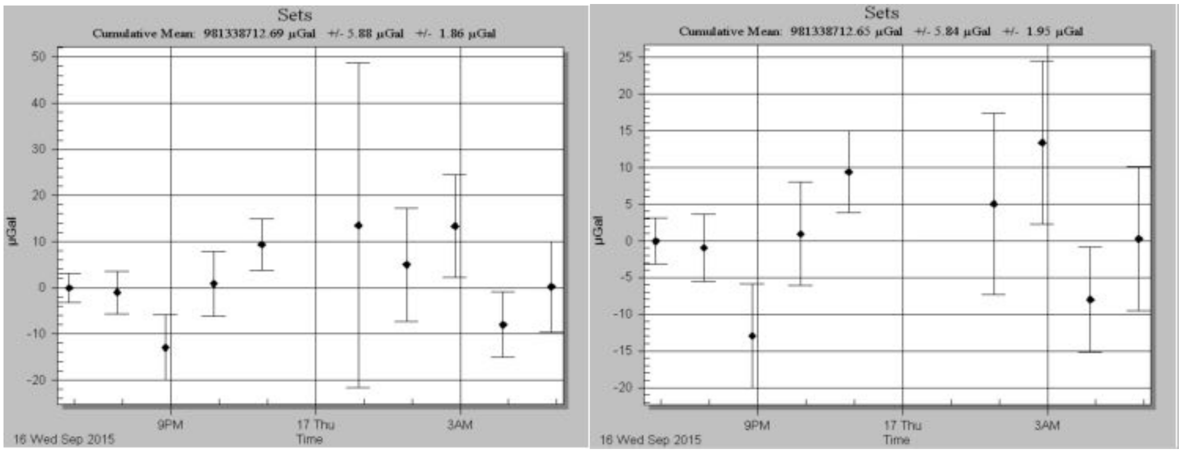

Figure 98: Absolute gravity per set without set no 6 (left) and without sets no 6 and 7 (right). The error bars indicate the set SD. Absolute gravity refers to 130 cm above floor level.

To reduce the absolute value of gravity from the instrument level to the marker at the floor, the local gradient of gravity was derived from relative gravity measurements at two different heights using the Scintrex CG5 relative gravimeter. Results are shown in Figure 99 and Figure 100. Over 135.95 cm, we found a gravity difference of 413 ± 3.9 (1σ) µGal, after removing values > 2σ. The corresponding local gravity gradient is 3.038 ± 0.029 (1σ) µGal/cm.

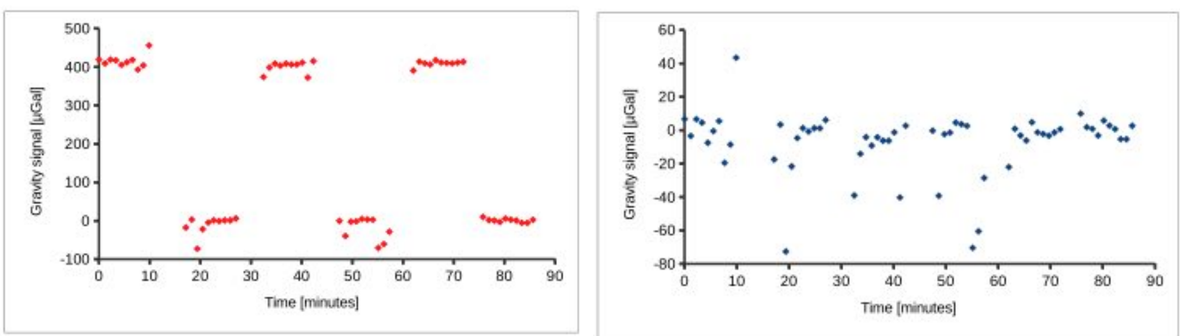

Figure 99: Left: Measured gravity difference at height 135.95 cm above floor level (tripod) and floor level. The mean is 413 µGal. Right: Scatter around the mean of 413 µGal.

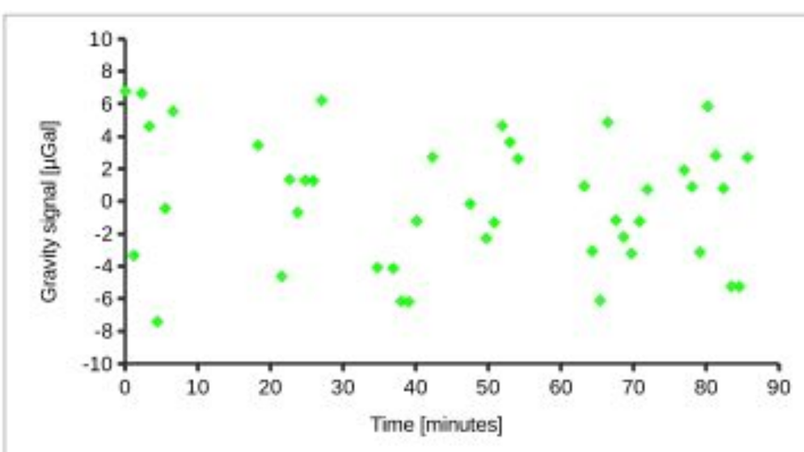

Figure 100: Scatter around the mean of 413 µGal after removing values > 2σ.

The uncertainty in the gradient of ± 0.029 (1σ) μGal/cm is larger than typically measured at other stations in the Netherlands. This can be explained again by the soft ground in combination with the windy conditions during data acquisition. Gradient measurements could be repeated at less windy conditions to better determine the vertical gradient. Final values are listed in Table 31.

	Value	Tolerance
Gravity at instrument level, 130 cm above floor	981 338 712.7 μGal	1.8 μGal
Gravity at ground level, 0 cm above floor	981 339 107.6 μGal	4.2 μGal
Local gravity gradient	-3.038 μGal/cm	0.029 μGal/cm

Table 31: Gravity values in the Overschild windmill.

11.2 Comparing absolute and relative gravity at Aurich, Overschild and Westerbork

Absolute gravity values 25 cm above ground for the three sites used in the relative survey are listed in Table 32.

Station	Gravity 25 cm above ground	Vertical gravity gradient	Uncertainty
Westerbork	981 308 993.9	-2.926	1.0
Overschild	981 339 031.7	-3.038	3.8
Aurich	981 356 664.5	-2.74	5

Table 32: Absolute gravity values at the three tie stations for the Groningen relative network. Values are in μGal or μGal/cm.

Relative gravity at the three absolute stations were obtained from the processing of the network, as described in Chapter 13, and using the scale factors listed in Table 22. The gravity differences are listed in Table 33. The general station uncertainty is 1 μGal (standard deviation) for relative values and thus 1.4 μGal for a station difference, such as between the absolute sites. Discrepancies between absolute and relative measurements are shown in the second rightmost column in Table 33. The relative gravity differences are all smaller than the absolute differences, with significant values for the two largest differences. This could be explained by:

1. The stations having a differential seasonal variation in signal from e.g. ground water of about -10 μGal. For instance, the water level could be lower in September 2015 for the Aurich measurement.
2. The scale factors for the CG5's are too low by a factor 3.3×10^{-4}.

Station	Absolute gravity difference	Uncertainty	Relative gravity	Uncertainty	Discrepancy between absolute and relative measurement	Uncertainty
404 Overschild - 402 Westerbork	30 037.8	3.9	30 033.7	1.4	5.1	4.1
401 Aurich - 404 Overschild	17 632.8	6.3	17 621.2	1.4	11.6	6.5
401 Aurich 402 Westerbork	47 670.6	5.1	47 654.9	1.4	15.7	5.3

Table 33: Gravity differences between absolute stations, measured by absolute and relative meters. All values are in μGal.

We have for the final processing used the Monschau calibration, while realizing there is an uncertainty in the scale factors at least as large as the discrepancy of 3.3×10^{-4}, which is much larger than the formal uncertainty of the calibration survey.

12 Station pairs with transfer measurements

Transfer measurements took place on daytime 8th, 9th, 11th, 12th, 27th and 28th of September, at 11 stations where the old location was on grass or had difficult access. New sites were chosen at 4.5-87 m distance from the old location. Gravity was measured alternating between the new and old location, with a total of five measurements. Two of the old stations were in 2015 in farmer's fields (#14 and #20), one was inside a hut belonging to the municipality and the remaining eight were inside fences of NAM sites. One station (#12) has the new location still inside the NAM fence, while the remaining seven NAM sites were moved to outside the fence, to make them more accessible during the main survey. The new stations are numbered with 500 added to the initial number (for example #4 was transferred to #504).

No	Station name	h_{78}	h_{96}	h_{15}	Subsidence 1996-2015	Δh Calculated local height change	h_{bm} height of benchmark
4	Tussenklappen	-0.43	-0.48	-0.545	-0.0077	0.012	0.019
504				-0.695			
6	Haren	0.50	0.47	0.450	-0.051	0.031	0.097
506				0.485			
7	Kooipolder	-0.28	-0.33	-0.482	-0.085	-0.067	N/A
507				-0.585			
10	Schildmeer	-0.85	-0.92	-1.217	-0.093	-0.204	0.091
510				-1.141			
11	Ten Post	-0.15	-0.25	-0.517	-0.135	-0.132	0.089
511				-0.666			
12	Delfzijl	0.06	-0.02	-0.294	-0.069	-0.205	0.100
512				-0.235			
14	Winsum	0.86	0.87	0.378	-0.043	-0.449	0.040
514				0.490			
16	Leermens	1.13	1.03	0.836	-0.117	-0.077	0.098
516				0.437			
18	Bierum	1.21	1.14	0.904	-0.099	-0.138	N/A
518				0.915			
20	Eenrum	1.64	1.61	1.441	-0.025	-0.143	0.081
520				1.537			
21	Usqert	1.73	1.68	1.451	-0.045	-0.184	0.045
521				1.461			

Table 34: Height changes of old stations that were transferred to new locations. All values are in meters relative to NAP.

Nine of the eleven old locations were in 2015 on grass. The NAM surveyors had prior to the 2015 survey marked the coordinates as given in the 1996 reports with wooden pins, and the height of the pins were surveyed in September 2015. These heights could be compared with the heights from previous surveys (1996 and earlier), shown in Table 34 (all values in meters). The height of the wooden pin above the solid surface (grass/tar) was small and set to zero for the calculations. Portable benchmarks (shown in Figure 39) were used for the gravity measurements on grass locations. The unit positions on top of the benchmark was kept the same on all repeats. The height of the benchmark with respect to the wooden pins were measured at each location, listed in Table 34. The various heights used in Table 34 are sketched in Figure 101, and described as:

- h_{96}, h_{88}, h_{84}, h_{78}: Height of old measurements, referred to NAP (Normaal Amsterdams Peil). These are found in Bilker (1996) and Geldern et al. (1999). Only h_{78} and h_{96} are listed in Table 34.
- h_{15}: Height in 2015 of wooden pin as reference for new measurement, referred to NAP. The NAM surveyors measured these.
- h_{bm}: Height of portable benchmark relative to wooden pin. The gravity crew measured these during the transfer measurements.
- $s_{2015-1996}$: the estimated/modeled subsidence between 1996 and 2015, provided by NAM. Negative numbers mean subsidence.

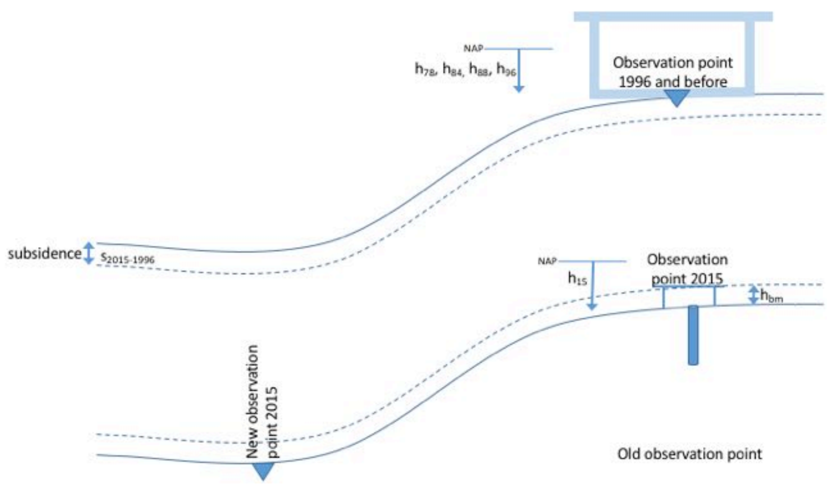

Figure 101: Sketch of the transfer of station values from "old location point" to new station established in 2015.

Heights were in 2015 determined based on levelling survey and time extrapolation of linear trends. Gravity benchmarks were leveled to other benchmarks in a leveling network which was measured in 2013. Then time extrapolation from 2013 to 2015 was done assuming linear trends. NAM expects the maximum extrapolation error to be in the order of 8 mm and error from leveling measurements to be about 5 mm.

When transferring gravity values between the old and new site, changes at the old site since 1996 which influence gravity has to be corrected for. These can be divided into free-air corrections from local height changes relative to the landscape around, e.g. caused by removal of a cabin floor, and the direct attraction from mass changes at the old site (e.g. removal of cabin and cabin floor). Surface subsidence caused by reservoir compaction is the same for both stations and shall therefore not be taken into account when calculating the gravity difference. However, subsidence data are needed to relate height measurements made in 1996 and 2015.

The local height difference between the observations in 1996 (and earlier) and the top of the wooden pin in 2015, which is not caused by subsidence, is denoted Δh. The relation between height measurements becomes:

$$h_{15} = h_{96} + s_{2015-1996} + \Delta h$$

Or rearranged:

$$\Delta h = h_{15} - h_{96} - s_{2015-1996}$$

A positive Δh means the local height has increased between 1996 and 2015 – mass has increased beneath the observation point, since we always measure on the soil/air interface.

The calculated Δh are listed in Table 34. Height difference is 3.1 cm at #6 Haren, where the floor is the same in 1996 and 2015, and only vertical movements of the floor bricks and measurement errors contributes. The maximum height change of 44.9 cm is at #14 Winsum, where an observation hut was transformed into a farming field. Nine of the 11 stations have negative Δh, which could be explained by cabin floors having been removed. Average height change is 16 cm for these stations.

These height changes transform to the following gravity corrections:

The height difference is likely caused by removal of soil - or the floor of the hut. We have applied a gravity correction assuming a vertical gradient of 233.2 μGal/m, which corresponds to a Bouguer correction with density 1800 kg/m^3, a high value for loose sand or clay, but on the low side for brick.

For the height of the portable benchmark above ground, h_{bm}, a free-air correction with gravity gradient of 308.6 μGal/m has been applied.

Some few gravity records were omitted from the processing as shown in Table 35. One linear drift correction was applied. With the exception of #16 Leermens, all stations have a repeatability better than 3 μGal. For the most part, three units were used (the portable benchmark has space for 3 gravimeters). Unit 11 show on average significantly poorer repeatability than the other units and was given weight 0.25 in the further processing. For station #12 Delfzijl, leaving measurement 3 out would increase the station difference by 0.9 μGal as compared to the value used in the final processing. Station #16 Leermens was the first set of measurements in the survey, and the 5 measurements required 3 ½ hour, with two long measurements at the start and the two last ones only 10 minutes long. Both units 10 and 11 show larger than usual scatter, and there are no obvious poor records. A 2nd order drift correction was assigned to unit 10 – the only non- linear drift correction of the transfer measurements. This is justified by being the first measurement in the campaign, of particularly long duration. For station #20 Eenrum, measurement 2 on unit 11 deviates about 9 μGal from the two others, and was edited out. This decreases the final offset by 0.6 μGal.

Station	Recording time (UTC)	Duration [hh:min]	Record length [min]	Units	Measurements (mmt) rejected in processing
4 Tussenklappen	September 11th 16:25-18:05	1:40	15-16	10, 11, 12	
6 Haren	September 12th 11:01-13:40	1:39	16-20	10, 11, 12	Mm0 u11, u12; recovery 25 nGal/s Mm3 u10; spike
7 Kooipolder	September 9th 12:50-16:01	3:11	15-17	10, 11, 12, 13	
10 Schildmeer	September 28th 9:46-12:15	2:29	20-22	10, 12, 13	
11 Ten Post	September 9th 6:56-10:02	3:06	20-22	10, 11, 12	
12 Delfzijl	September 11th 13:34-15:19	1:45	15-17	10, 11, 12	(Mm3 all units; tilts were leveled in the middle of the record)
14 Winsum	September 27th 9:56-12:45	2:49	20-25	10, 12, 13	
16 Leermens	September 8th 08:10-11:34	3:24	10-53	10, 11, 12	
18 Bierum	September 8th 13:25-16:06	2:41	15-27	10, 11, 12, 13	
20 Eenrum	September 12th 16:44-18:19	1:35	15	10, 11, 12	Mm2 u11; 9 μGal deviation
21 Usqert	September 28th 06:28-08:47	2:19	20-22	10, 12, 13	

Table 35: Measurement summary of the transfer stations. "Mmt" is an abbreviation for "measurement".

Measured gravity changes are listed with uncertainties in the first two data columns of Table 36. Gravity changes estimated from height changes are also listed. The third data column comes from local height changes, Δh, multiplied by the Bouguer gradient of 225 µGal/m. Next column is the effect of the benchmarks being above the ground and wooden pin, and here the free-air gradient is multiplied by h_{bm}. The next column is estimated gravity changes from removal of the huts. The basis for these calculations are shown in the next section. Stations 11 and 16 were inside control room buildings that were completely removed, and a 10 µGal gravity change is roughly estimated. These changes are summed (columns 2, 4, 5 and 6) in column 7. The values shall be added to the old data as corrections. Uncertainties (standard deviations) arising from lateral or vertical position estimates and from attraction of buildings are estimated in the rightmost columns in Table 36. The last column is the RMS sums of these uncertainties. Stations 11, 14 and 16 have the largest uncertainties, related to either the complete removal of the control room building or some large lateral position uncertainty.

Station	Gravity difference new-old	Uncer-tainty	Δg from local height change at old station	Δg from bm height	Δg from building change	Δg to be added to old station values	Uncer-tainty from lateral position	Uncer-tainty from height change	Uncer-tainty from building	Sum positional uncertainty at old station
4 Tussenklappen	33.3	0.4	-2.8	-5.9	5	29.6	5	5	2	7
6 Haren	33.6	2.1	-7.2	-30.1	0	-3.7	0	5	0	5
7 Kooipolder	27.8	1.8	15.6	N/A	5	48.4	5	5	2	7
10 Schildmeer	35.8	1.0	47.6	-28.1	5	60.3	5	7	2	9
11 Ten Post	56.0	0.8	30.8	-27.4	10	69.4	12	6	5	14
12 Delfzijl	21.7	0.9	47.8	-30.8	5	43.7	5	7	2	9
14 Winsum	-19.4	0.9	104.7	-12.3	5	78.0	5	12	2	13
16 Leermens	200.2	2.3	18.0	-30.1	10	198.1	12	5	5	14
18 Bierum	21.8	1.7	32.2	N/A	5	59.0	5	6	2	8
20 Eenrum	7.8	1.5	33.3	-25.0	5	21.1	5	6	2	8
21 Usqert	-31.2	1.1	42.9	-13.7	5	3.0	5	7	2	9

Table 36: Gravity changes measured at transfer sites in 2015, as well as corrections to be added to the old site values. All values are in µGal.

12.1 Gravity effect of removal of huts

Twelve gravity stations in 2015 (#4, 5, 7, 9, 10, 12, 13, 14, 18, 20, 21, 22) were compared with old locations that were inside observation well cabins. These were removed between 1996 and 2015. Only at station #6 Haren (Figure 6) is the hut still in place. A picture of such a hut is shown in Figure 102. Marcin Glegola at Shell has calculated the gravity attraction from the cabin for an observation point inside.

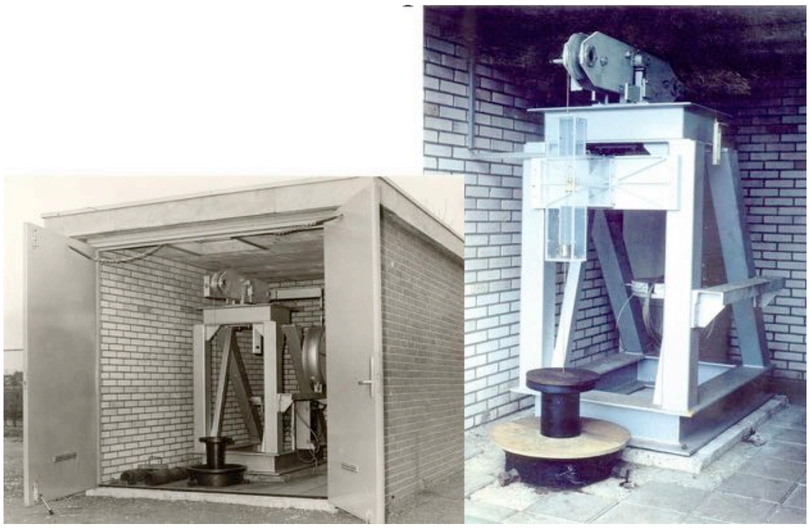

Figure 102: Cabin photograph and shallow compaction well inside the cabin (source: NAM).

A density of 2000 kg/m^3 was used for the brick walls, and 2400 kg/m^3 for the concrete roof (Figure 103). Weight of the installation inside the cabin (compaction well head) and cabin door is neglected. The modeling is done with prisms of 0.1 m × 0.1 m × 0.1 m and accurate analytical calculations from the model. The computation result is a gravitational attraction of about 5 μGal. Hence 5 μGal has been added to the old data at these stations.

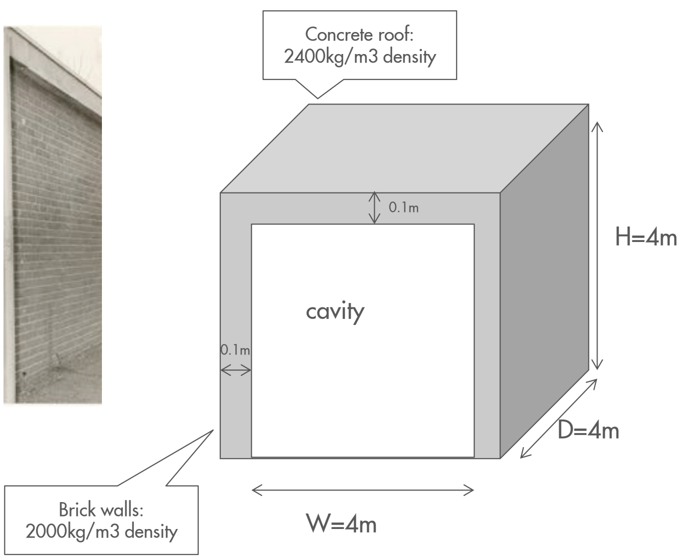

Figure 103: Density-structure model of the cabin (from Marcin Glegola, Shell).

The cabin floor is slightly higher than the outside ground, as can be seen from Figure 102. This agrees with reduced heights of all the stations in 2015 (Δh in Table 34). For the stations without a gravity transfer measurement, a calculation of the height change effect on gravity is required, and for that a density estimate of the removed floor. In our calculations we have used density 2200 kg/m^3, giving a vertical gravity gradient of 216.4 μGal/cm.

12.2 Analysis of height measurements for stations without transfer measurements

The sites that have experienced surface changes, 4 NAM sites with observation huts removed, and two railway stations, are shown in Table 37. Height reductions are calculated as measured height change minus modelled subsidence, and are negative for the four NAM sites; from -2.8 cm and up to -21 cm (column seven in Table 37). This is likely due to lowering of the surface when the observation hut floors were removed between 1996 and 2015. The floor at the railway station in Groningen is 3.8 cm higher in 2015 than the previous heights and subsidence predicts. Here the floor has been renovated since 1996, as is evidenced by Figure 25, and comparison of floor levels on the photographs suggest a rise of about that size. The location in Assen railway station seems from photo to be the same as in the 1990's, only on the other side of a window. This agrees with very small measured height changes.

Station	h_{78}	h_{96}	h_{15}	h_{15}-h_{96}	s_{15-96}	Deviation measurements-model h_{15}-h_{96}-s_{15-96}	Δg_{height} [µGal]	Δg from building change [µGal]	Δg to be added to old station values [µGal]	Uncertainty from height change [µGal]
5 Roode Til	-0.60	-0.64	-0.918	-0.278	-0.068	-0.210	47.2	5	52.2	6
9 Ten Boer	-0.34	-0.42	-0.582	-0.162	-0.077	-0.085	19.1	5	24.1	5
13 Stedum	1.18	1.03	0.887	-0.143	-0.115	-0.028	6.3	5	11.3	4
22 Uithuizermeeden	1.85	1.76	1.618	-0.142	-0.080	-0.062	13.9	-1.5	12.4	5
30 Groningen NS	3.40	3.40	3.399	-0.001	-0.039	0.038	-8.5	0	-8.5	4
33 Assen NS	11.15	11.15	11.151	0.001	-0.004	0.005	1.1	0	1.1	4

Table 37: Height changes at NAM sites and railway stations that did not have transfer measurements. All values in meters.

Gravity changes caused by the local height changes (before any subsidence correction) are calculated similar to the transfer measurements; multiplying the height changes with a gravity gradient of 224.8 µGal/m, assuming a soil density of 2000 kg/m^3. The estimated gravity increase is shown in column eight in Table 37. At the NAM sites, huts have been removed, and an estimated 5 µGal shall be added, shown in column nine in Table 37. For #22 Uithuizermeeden, large oil tanks have been built since 1996, with an estimated upward gravity attraction of 6.5 µGal (page 28). This has been added (as a negative correction) to station #22. The total correction to be added to old data, to compare with the 2015 measurements, is shown in column ten in Table 37. Uncertainties are given in the rightmost column, estimated from the following standard deviations: 10% in vertical gravity gradient, 1 cm in height change, 3 µGal in gravity effect of observation hut removal and 3 µGal from gravity effects of oil tanks at #22 Uithuizermeeden.

Sites where the top surface is unchanged are listed in Table 38. These are, with the exception of #19 Uithuizermeeden church, within 1.6 cm of expected heights, which is close to the measurement accuracy and serves as confirmation that the new sites are at the correct spots. Re-position variations contribute to the height changes. Annerveen has remained unchanged since 1978, with a marker still in the floor (Figure 3). The station at Groningen Sint Fraciscuskerk was moved about 18 m from the nominal coordinates to just in front of the entrance of the church – two steps up. This is where other church stations have been, and seems to have been common practice for past gravity crews. The close height agreement confirms this choice of site. The height of the Uithuizermeeden church station was measured to 2.770 m in 2015. At the same time, a model gives 7.9 cm subsidence since 1996, causing a discrepancy of 13.9 cm. This is far above any uncertainty, and the cause of this has not been resolved. We have used the height stipulated from the 1996 measurement + subsidence for the 2015 height in the time-lapse gravity processing, giving a value of 2.631 m instead of 2.770 m. Agreement is otherwise good for the five sites that can be controlled. Deviations may be due to observational uncertainty and different than predicted subsidence here. No height corrections have been applied to these sites.

Station	h_{78}	h_{96}	h_{15}	h_{15}-h_{96}	$s_{15\text{-}96}$	Deviation measurements-model h_{15}-h_{96}-$s_{15\text{-}96}$	Δg_{height}
2 Gasselte church	17.84	17.84	17.829	-0.011	-0.003	-0.008	0
3 Annerveen	2.05	2.00	1.957	-0.043	-0.030	-0.013	0
8 Groningen Sint Fraciscuskerk	0.94	0.90	0.833	-0.067	-0.062	-0.005	0
15 Middelstum church	3.07	2.97	2.899	-0.071	-0.076	0.005	0
17 Garsthuizen garage	2.20	2.06	1.943	-0.117	-0.101	-0.016	0
19 Uithuizermeeden church	2.81	2.71	(2.770)	0.060	-0.079	(0.139)	0

Table 38: Height changes at six public sites. All values are in meters.

12.3 OM's at Gasselte and Wagenborgen

The two OM's were measured in both 1996 and 2015. In 1996 the gravimeter was placed inside the hole, while in 2015 the three meters were just fitted on top of the plate (Figure 104). The diameters of the holes are between 51 and 59 cm. A pin in the center of the hole is rising a few cm's above the ground. The height of the gravimeter during the 1996 observations is not known; it may have been put on a tripod, as the center pin in the hole could prevent placement on the bottom of the hole. Depths to both the top of the pin and the flat bottom from the top surface were measured in both holes, with values shown in Table 39. The hole is sketched in Figure 105.

Figure 104: Gravity measurements at OM, in 1996 (left) and in 2015 (right).

Station	35 Gasselte OM	34 Wagenborgen OM
Height values from 1996	14.17	0.60
Height values from 2015 surveying	15.006	1.182
h_{hole}, height difference from bottom to top, measured by Quad in 2015 [m]	0.842	0.750
Height difference from pin to top, measured by Quad in 2015 [m]	0.783	0.736
Gravity correction [μGal]	205.1	187.2

Table 39: Heights for the OM's, and calculated gravity difference between a measurement inside or at the top, in meters.

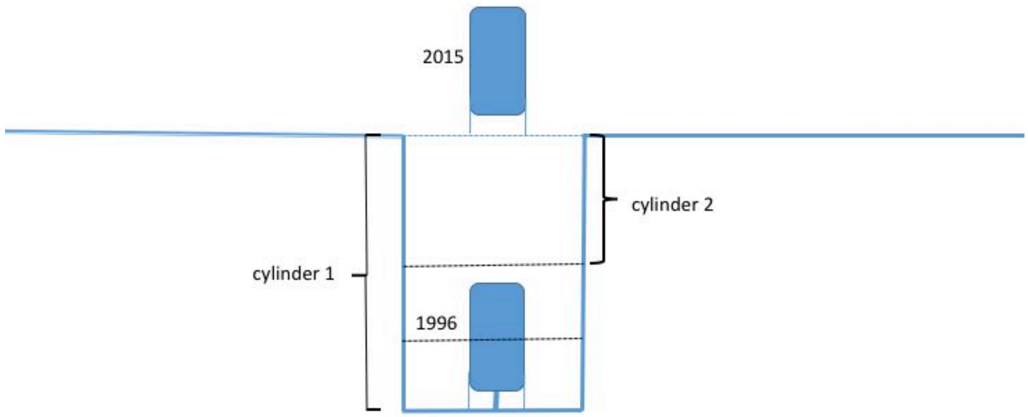

Figure 105: Sketch of the OM hole and the gravimeter positions in 1996 and 2015.

The gravity change between the two measurement positions can be calculated by decomposing into:

1. A free-air correction from the 2015 measurement height to the soil surface; $h_{sensor2015} \times 308.6$ μGal/m.
2. A double Bouguer correction from the soil surface and down to the 1996 measurement height; $(h_{hole} - h_{sensor,\ 1996}) \times 141$ μGal/m.
3. The attraction of a cylinder of soil with radius 27.5 cm, from the surface and down to the bottom of the hole, at the 2015 measurement point (cylinder 1 in Figure 105). This contributes negatively to the 2015 measurement, but positively to the 1996-2015 difference.
4. The attraction from a cylinder starting the same height above the 1996 observation point as the observation height over the bottom of the hole (which is unknown) and up to the top of the hole (cylinder 2 in Figure 105). This contributes positively to the 1996 measurement.

The gravity difference 1996-2015 is then the sum of these four positive numbers. This value is subtracted from the 1996 data to compare with the 2015 values.

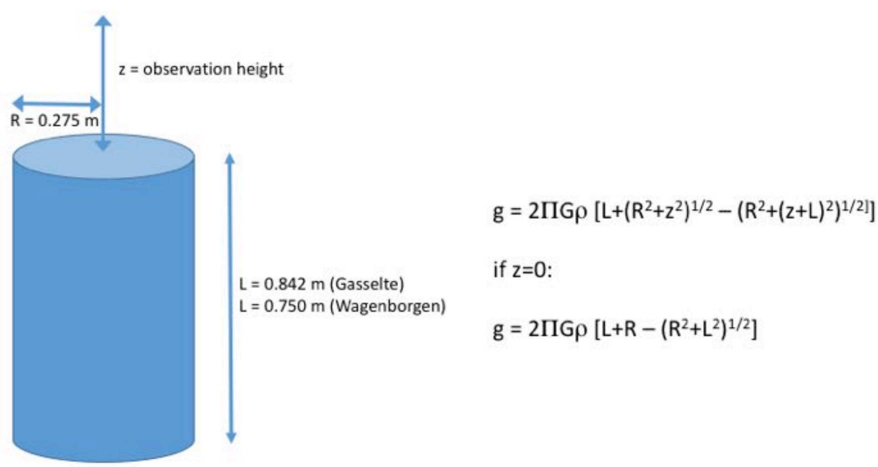

Figure 106: Gravity attraction from a cylinder, measured at a point along its axis.

The formula for gravity attraction from a cylinder at its axial extension is shown in Figure 106. We assumed soil density 2000 kg/m^3 in the calculations, giving a (double Bouguer) gravity gradient of 141 μGal/m in the hole. The height of the sensor above the ground was 0.25 m in 2015.

Station	Assumed observation height in 1996 [cm]	Free-air correction	Double Bouguer correction	Cylinder 1 from 2015 point	Cylinder 2 from 1996 point	Sum
35 Gasselte	0.0	77.1	118.7	7.3	19.4	222.5
	25.0	77.1	83.5	7.3	5.0	172.9
	38.7	77.1	64.2	7.3	1.0	149.6
	42.1	77.1	59.4	7.3	0	143.8
34 Wagenborgen	25.0	77.1	70.5	7.0	4.2	158.8
	38.7	77.1	51.2	7.0	0	135.3

Table 40: Calculated gravity changes between observations in the OM hole and on top of it. All values are in µGal.

Stations #2 Gasselte and #35 Gasselte OM are only 76 m apart, and both were measured in 1996 and 2015. They are expected to have the same variations in gravity from reservoir and ground water, leaving only the different vertical position with respect to the OM hole as variable. The #35 - #2 difference can thus be used to calculate the top-bottom difference. The difference was 615.5 µGal in 2015 and 765.1 µGal in 1996. The decrease of 149.6 µGal fits with an observation height of 38.7 cm. We have used the 149.6 µGal figure for the correction at #35 Gasselte, which then gives no new information from the reservoir. The hole at station #34 Wagenborgen is 9.2 cm shallower than #35 Gasselte, giving a 14.3 µGal smaller gravity change. The value of 135.3 µGal was subtracted from the 1996 data to compare with the 2015 data.

13 Processing of 2015 data

All survey data have been processed in QuadPro, Quad Geometrics' proprietary software for time-lapse microgravity data. The noise level in the raw data (RMS scatter) is shown in Figure 107. It can vary by an order of magnitude as a function of time. Most of the noise is microseism, caused by ocean waves hitting the coast, and thus varying with the sea-state offshore the Netherlands. The noise level also decreases with distance from the coast (Figure 108), with #22 Uithuizeermeden as the noisiest.

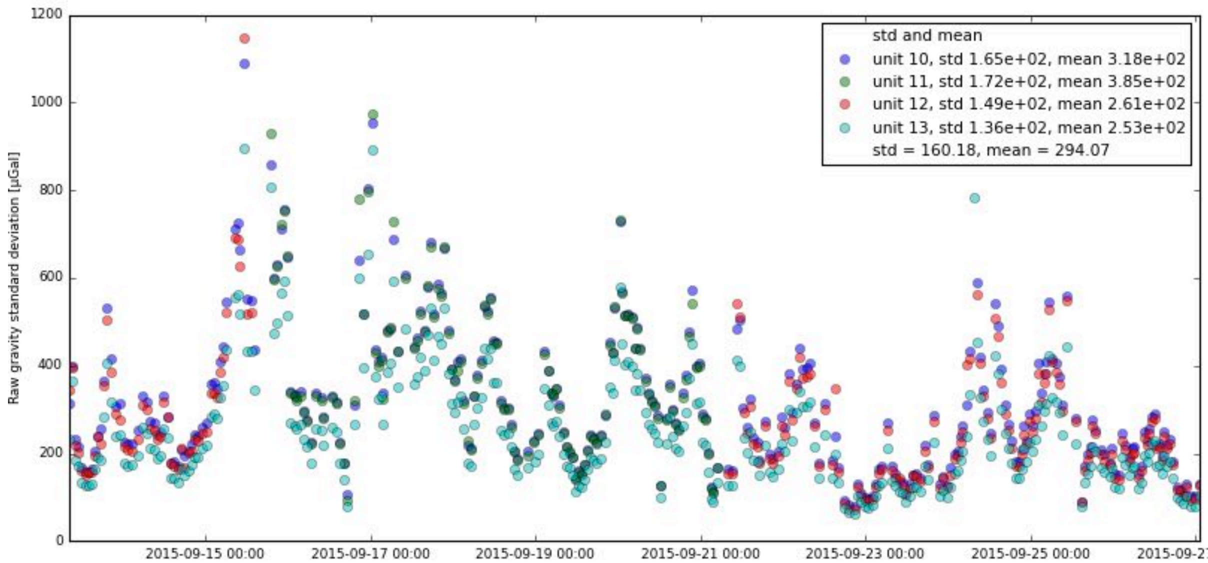

Figure 107: RMS scatter of each raw record as function of survey time.

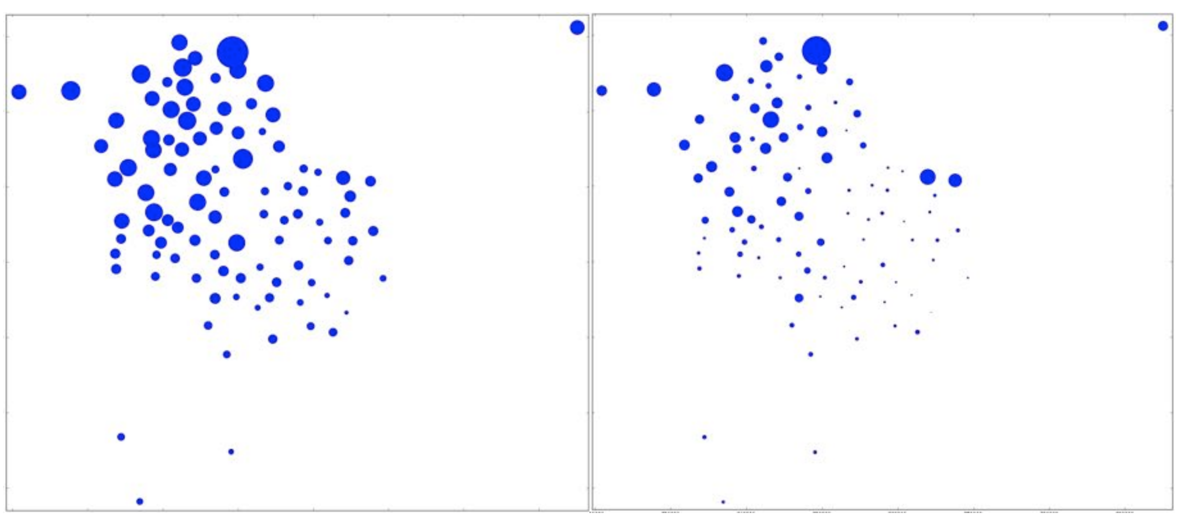

Figure 108: Average noise level for each station, in map view. Left: RMS scatter. Right: Amplitude of peak frequency. Circle radii are proportional to noise values.

13.1 Editing, low-pass filtering and time-series stability

Of the 309 measurements and 926 records, 264 were edited (29%). Re-leveling during acquisition could cause up to 3-5 μGal "spikes" in the low-pass filtered data, particularly for unit 11.

The time-series from unit 10 has often sudden level shift of about 2-4 µGal, of unknown causes. Units 11 and 12 has on average a stronger recovery than units 10 and 13. Curvature is often seen when recovery is strong, reducing the gradient during the 20 minutes of measuring. In cases where this has been clear, the first parts of the records were removed in the editing.

One complete measurement was taken out due to bad performance on all units: Measurement 45, at station #404 Overschild, has low-pass standard deviations of 7-10 µGal. The three units are coherent, making an external noise source likely. This measurement was made at 9 am local time Tuesday September 15th, and no particular event is mentioned in the operator's logbook. Only two relatively week earthquakes in Japan of M4.8 and M4.6 occurred in that time interval. Although cumulative sums show stability within a few µGal, both units 10 and 13 are outliers of 16-18 µGal in the repeatability plot.

Starting with measurement #77 (Figure 109), the Chilean earthquake affected at least five measurements. This was also seen in the absolute gravity data from Overschild (page 84). The low-pass filtered time-series standard deviations for a period of 20 hours are shown in Figure 110. While low-pass amplitudes are up to 80 µGal, peak frequency is about 5×10^{-2} Hz (period of 20 s). Cumulative averages are stable within a few µGal, and the measurements are not outliers in the repeatability plot. Therefore, all these records were kept in the processing.

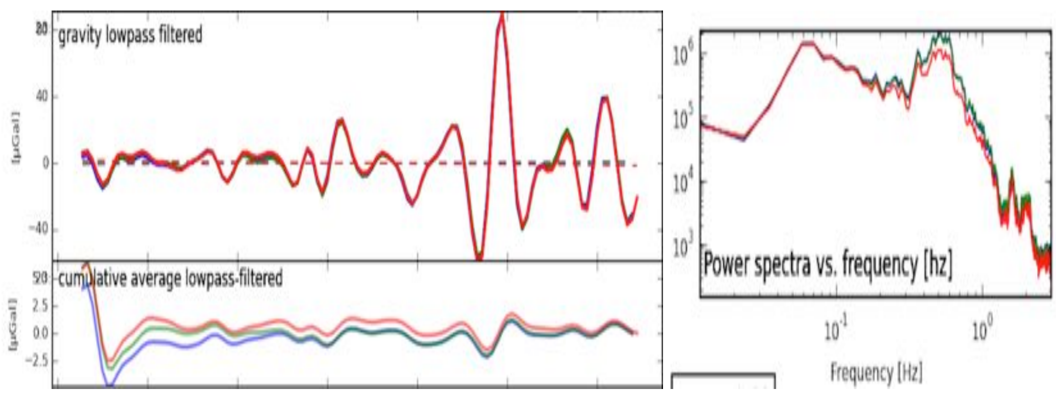

Figure 109: Low-pass filtered 20 minutes measurement #77 (above left), cumulative sum (below left) and power spectrum (right).

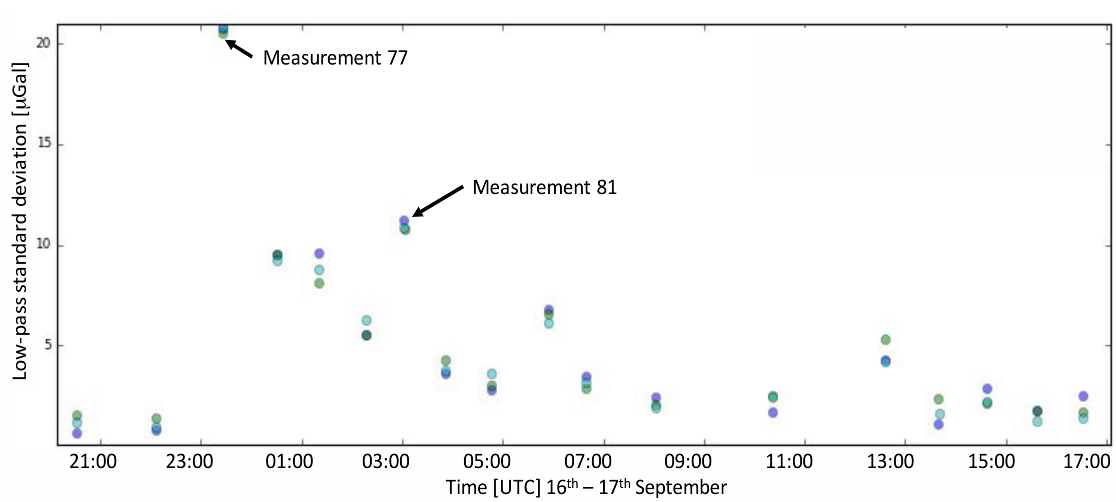

Figure 110: Low-pass filtered time-series standard deviation of records affected by the Chilean earthquake.

Measurement #238 is odd for unit 12. CG5 temperature is highly anomalous, and gravity drift is -49 nGal/s. This is probably due to low voltage on the top battery which caused the heaters to turn off briefly, which was realized during the recording. The record was omitted from further processing.

The standard deviation of the samples in each low-pass filtered time series is shown for all records, as a function of survey time, in Figure 111. The first eight measurements after the Chilean earthquake hit have been removed from the plot and from the average values shown in Table 41. Units 12 and 13 have the lowest average and scatter, while unit 11 has the least stable time series.

	Unit 10	Unit 11	Unit 12	Unit 13
Average	1.7	2.0	1.3	1.3

Table 41: Stability (RMS scatter) of low-pass filtered time series, in µGal. Survey-average values.

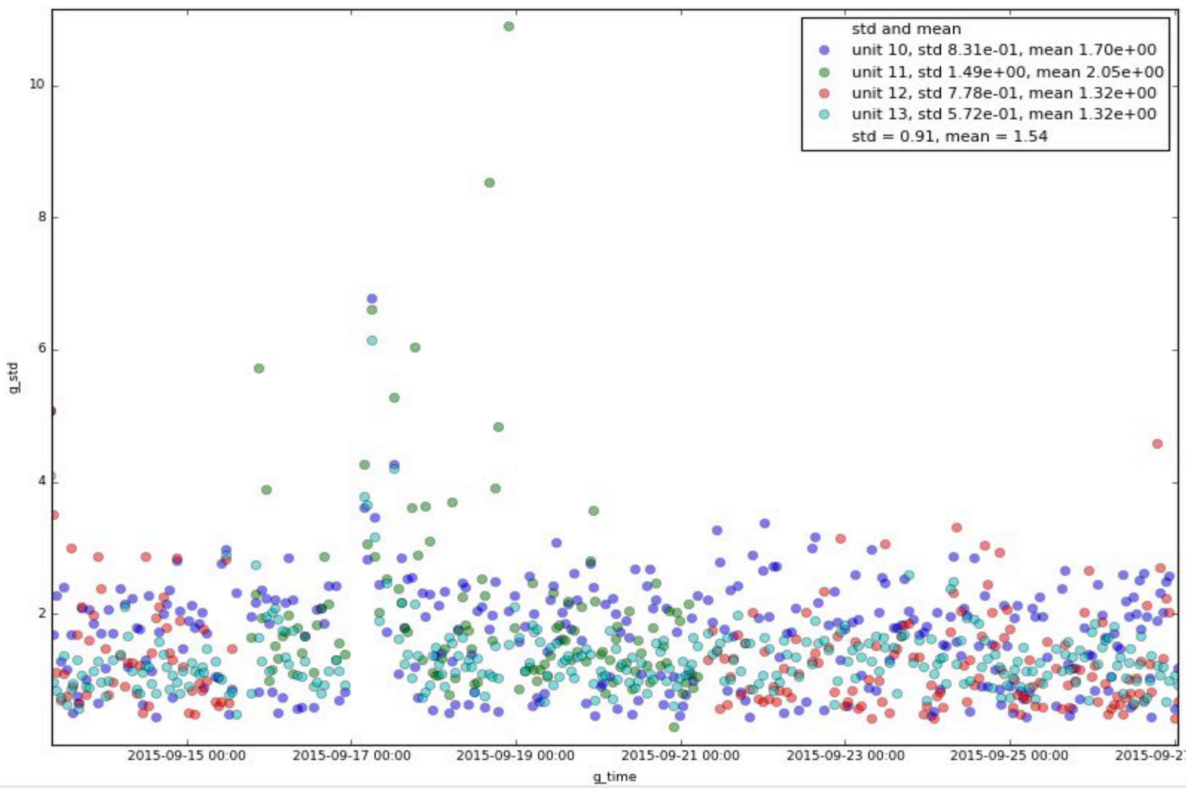

Figure 111: Standard deviations of samples in low-pass filtered time series, as function of survey time.

Calculated linear recovery values are shown in Figure 112, and survey-average values are listed in Table 42. All units have a slight trend of decreasing recoveries with time, and there is apparently some correlation between neighboring measurements (in time). Unit 13 has much lower scatter in recovery than any other unit; 1.5 nGal/s, which corresponds to 1.8 µGal over 20 minutes. Several measurements for units 11 and 12 (18 and 7 respectively) have recoveries exceeding 10 nGal/s.

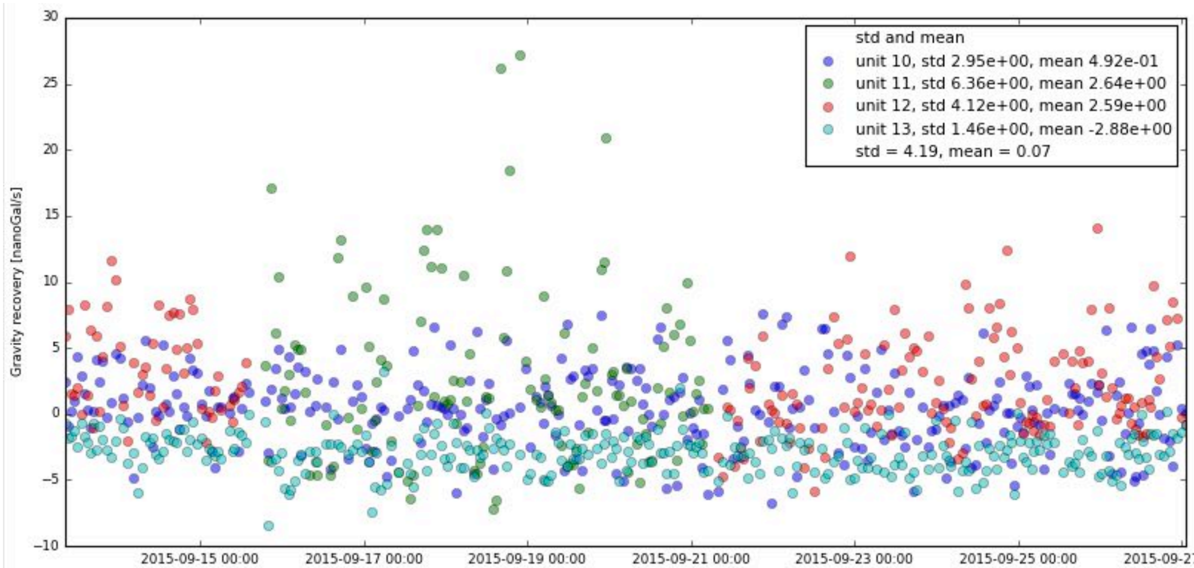

Figure 112: Recovery (in nGal/s) as a function of survey time for all records.

	Unit 10	Unit 11	Unit 12	Unit 13
Average	0.5	2.6	2.6	-2.9
Standard deviation	3.0	6.4	4.1	1.5

Table 42: Recovery averages and scatter for each unit.

13.2 Tilt corrections

The average tilt corrections were about 0.3 µGal for all units. Only 8 records had average correction exceeding 2 µGal. The 3 first records on unit 10 are among these, caused by the tilt setting in the recording software not being updated with the pre-survey tilt calibration.

The fine tilts were drifting on many of the asphalt stations. This required re-leveling more times during a record. This re-levelling caused disturbances on the gravity records, seen in the low-pass filtered time series.

The ground was tilted up to a maximum of 3.5° (station #302 Oudeschip). Also stations #33 Assen and 117 Westerwijtwerd church had tilts exceeding 2°. Average ground tilt was about 1°.

13.3 Drift corrections

Unit 10 and to a less degree unit 13 have a significant second order drift. A simple drift solution with 2-4 intervals, 2 tares and second-order segments are shown in Figure 113. Unit 11, and to some degree unit 12, show clear diurnal residuals, while units 10 and 13 behave close to a second-order drift, with RMS residuals of about 4.3 µGal.

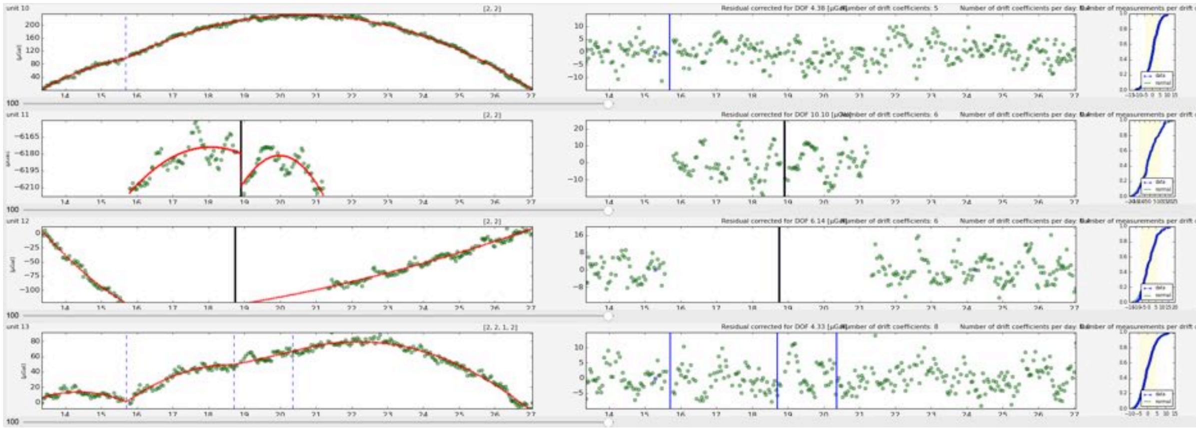

Figure 113: Left: Green dots are gravity measurement residuals from station means for units 10, 11, 12 and 13 (top to bottom), after linear trend has been removed. X-axis is survey time. Red curves show the drift correction beyond one linear term. Right: Measurement residuals after all drift corrections have been applied; that is the difference between the red line and the green dots in the left panels. A minimal drift solution with 7 coefficients per unit has been used in this case..

Adding a novel sine function drift adjustment is shown in Figure 114. This lower the RMS residuals for all units, and particularly for units 11 and 12. Best-fit amplitudes are shown in Table 43, ranging from 2.2 µGal for unit 13 to 11 µGal for unit 11.

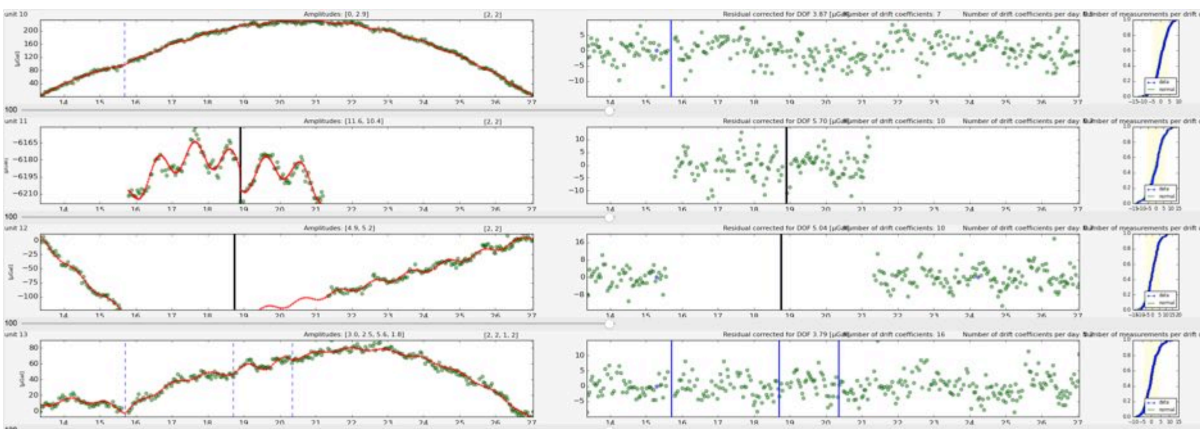

Figure 114: A minimal drift solution as in Figure 113, but with a periodic drift added for all drift segments.

<table>
<tr><th>Unit</th><th>Unit repeatability after minimal drift coefficients (Figure 113)</th><th>Measurement repeatability after minimal drift coefficients (Figure 113</th><th>Unit repeatability after additional periodic drift correction (Figure 114)</th><th>Amplitude of the fitted 24h sine drift function [µGal]</th><th>Measurement repeatability after additional periodic drift correction (Figure 114)</th></tr>
<tr><td>10</td><td>4.4</td><td rowspan="4">3.3</td><td>3.9</td><td>2.7</td><td rowspan="4">2.9</td></tr>
<tr><td>11</td><td>10.1</td><td>5.7</td><td>11</td></tr>
<tr><td>12</td><td>6.1</td><td>5.0</td><td>5.2</td></tr>
<tr><td>13</td><td>4.3</td><td>3.8</td><td>2.2</td></tr>
</table>

Table 43: Repeatability before and after periodic drift adjustment.

We removed all records with recoveries larger than 10 nGal/s; 17 on unit 11 and 8 on unit 12. This improved RMS residual from 5.7 to 5.3 µGal for unit 11 and from 5.0 to 4.7 µGal for unit 12. Further we applied recovery correction factors, found by optimizing the RMS residuals, and quality controlled by cross-plotting residuals and recovery.

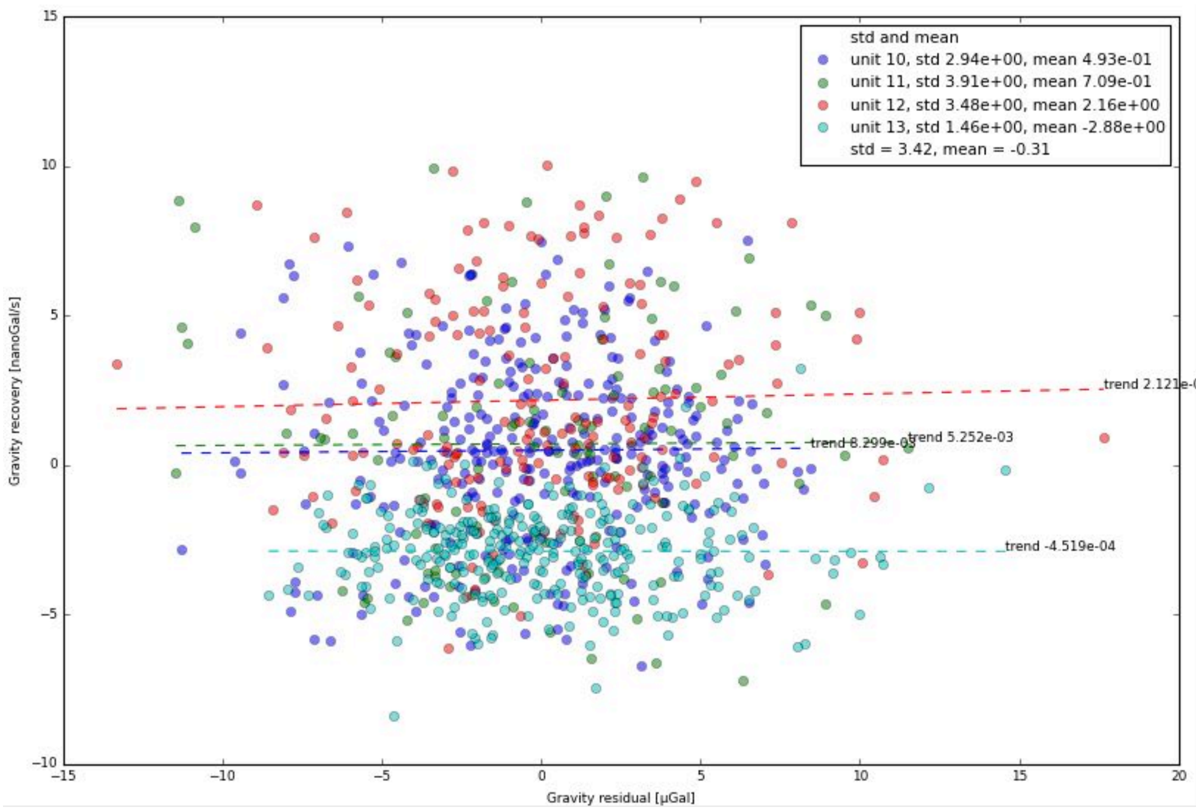

Figure 115: Recovery vs. residual after omitting recoveries > 10 nGal/s (on units 11 and 12) and applying the minimal drift solution from Figure 114 and linear recovery corrections.

The next step was to remove 6 outliers, listed in Table 44.

Measurement	179	49	179	203	204	228
Unit	13	10	12	12	12	12

Table 44: Outliers removed from further processing.

The final drift corrections are shown in Figure 116 and Figure 117, and some key numbers for the drift inversion are listed in Table 45. Unit 10 has been given weight 0.8, unit 11 weight 0.2, unit 12 weight 0.6 and unit 13 full weight in the solution. Diurnal period drift adjustments were run for the main time intervals of units 11 and 12, with amplitudes of about 12-15 and 3 µGal, respectively. Two complete measurements were removed in this phase; #0 at station 404 and #179 at station 22. Station residuals after this drift correction, using a joint inversion, are shown in Figure 117. Unit 13 has the best repeatability, with unit 10 and 12 not far behind.

The measurement repeatability is shown in Figure 118. The repeatability (standard deviation) normalized for drift coefficients is 1.7 µGal. Uncertainty in station values is then, when averaging 3 independent visits, estimated at about 1.12 µGal (standard deviation). The uncertainty estimates for each station is shown in Figure 119.

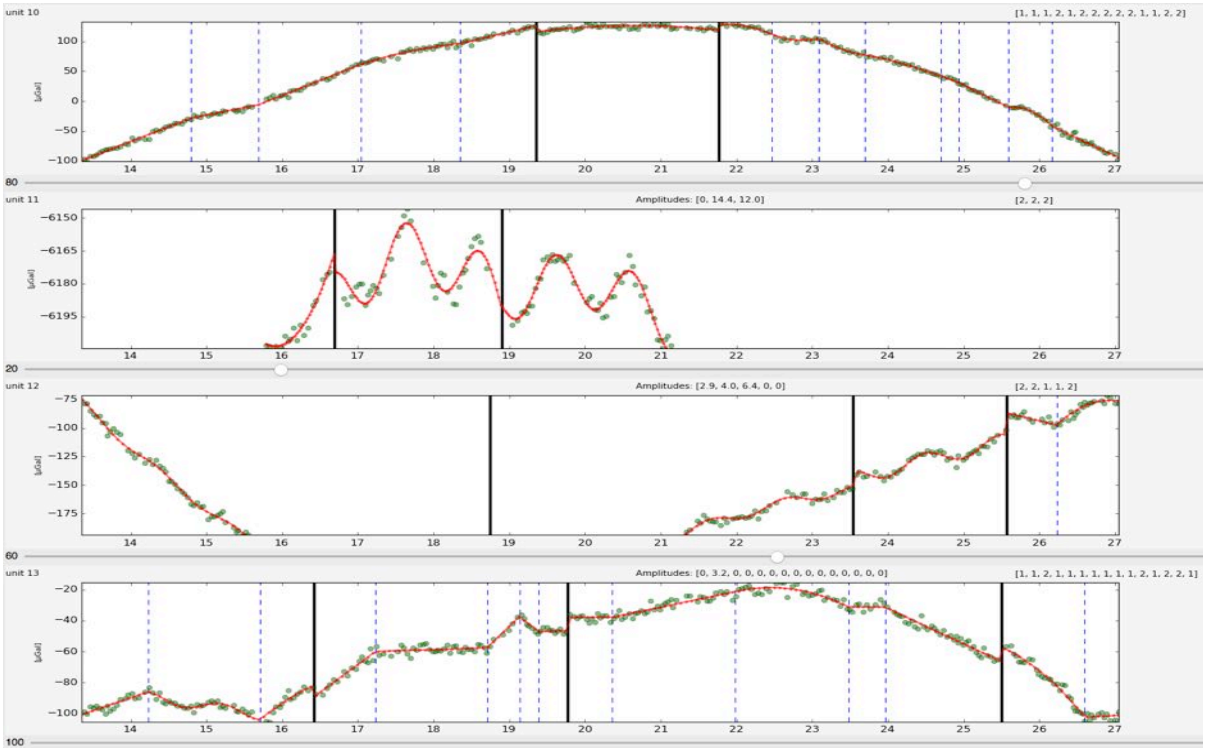

Figure 116: Final drift correction. Green dots are gravity measurement residuals from station means for units 10, 11, 12 and 13 (top to bottom), after linear trend has been removed. X-axis is survey day. Red curves show the drift correction beyond a single linear term. Tares are shown as solid vertical lines and drift segment boundaries without tares as hatched blue vertical lines.

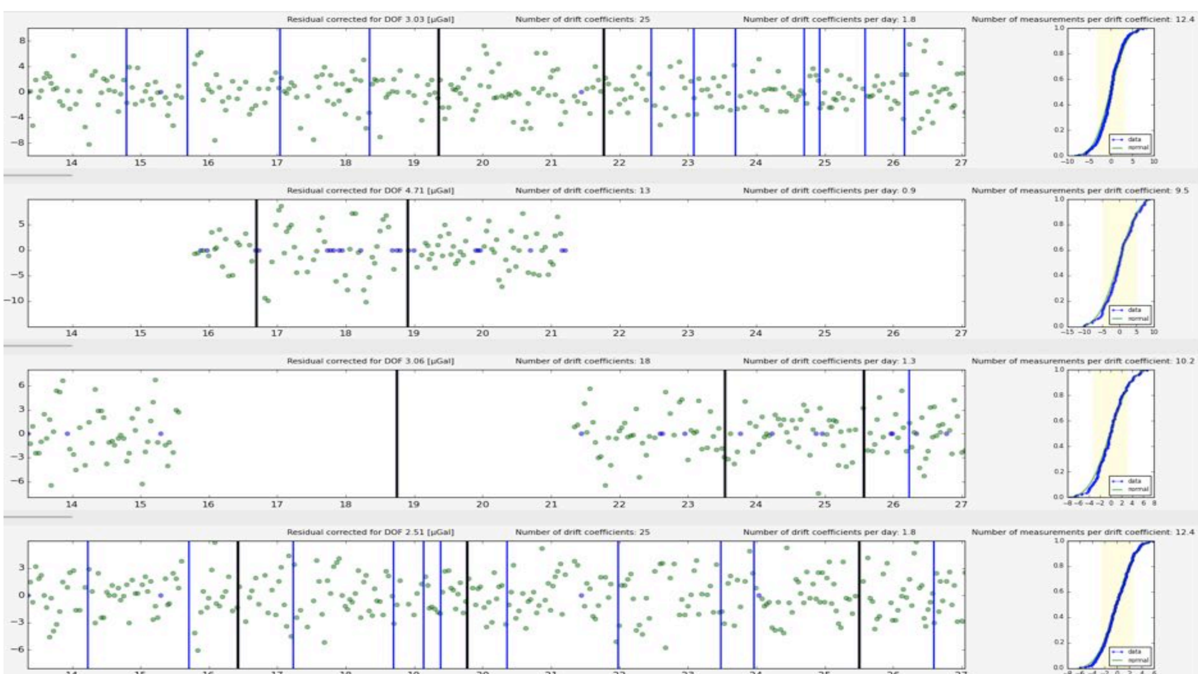

Figure 117: Final drift correction. Measurement residuals after all drift corrections have been applied; that is the difference between the red line and the green dots in Figure 116. Gravity values after detailed drift correction.

	Unit 10	Unit 11	Unit 12	Unit 13
Recovery factor	0	-0.6	-0.55	-0.5
Number of records in total	309	124	184	309
Number of record omitted	3	21	15	4
Weight	0.8	0.2	0.6	1.0
Number of drift coefficient	25	13	18	25
Number of measurements per drift coefficient	12.4	9.5	10.2	12.4
Unit repeatability	3.0	4.7	3.1	2.5

Table 45: Key numbers for the drift inversion.

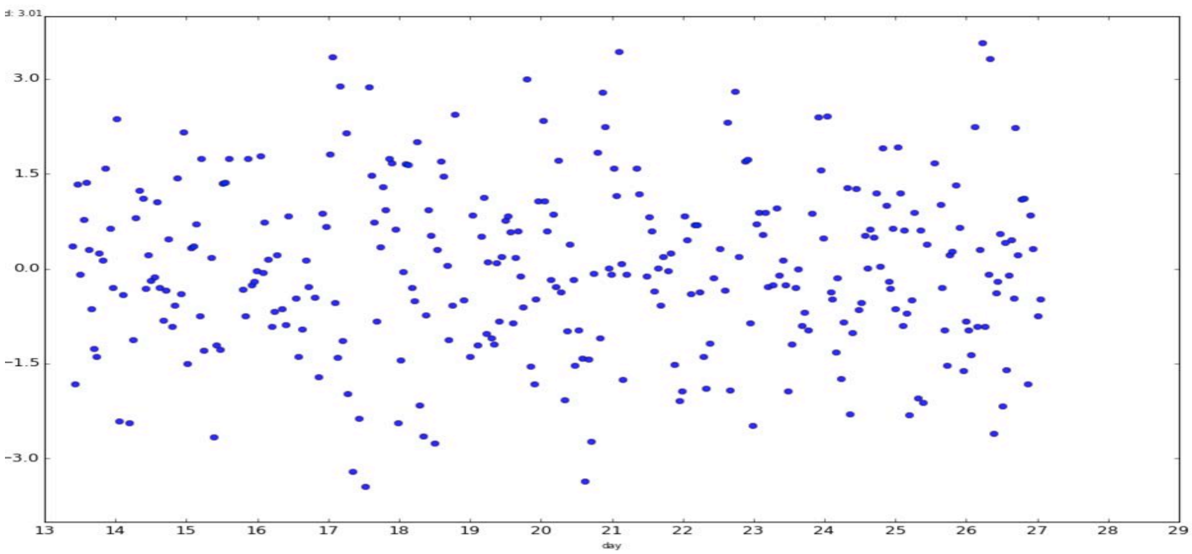

Figure 118: Measurement repeatability. Standard deviation is 1.7 µGal when taking the drift coefficients and degrees of freedom into account.

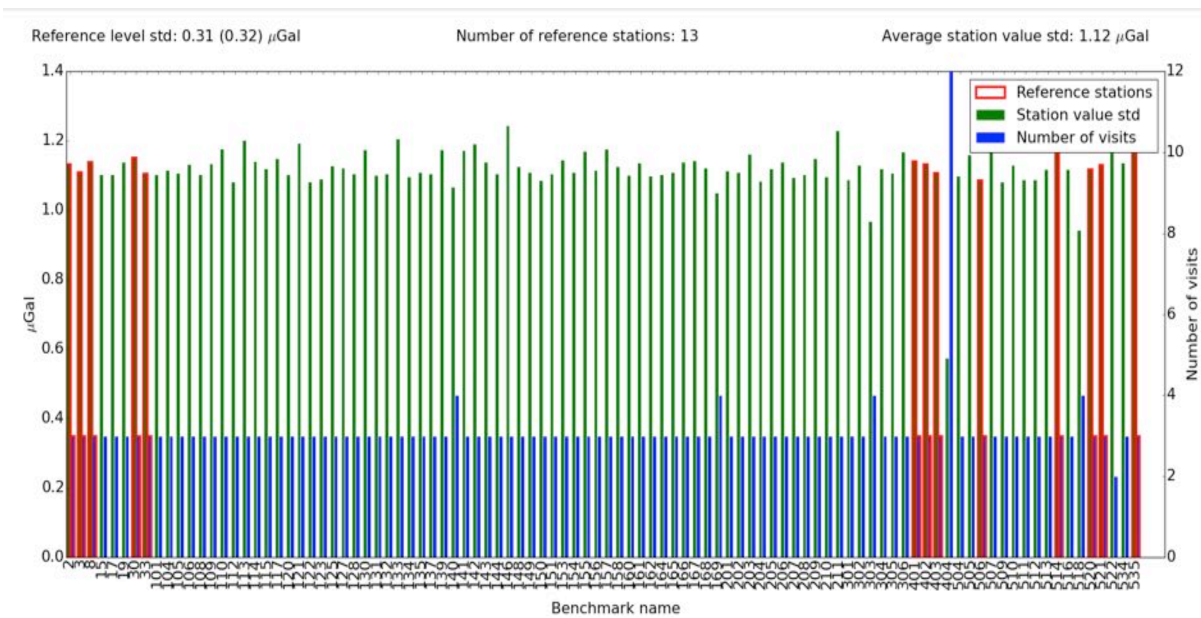

Figure 119: Estimated station uncertainties (green) and number of valid visits (blue).

13.4 Air pressure correction

Air pressure has a well recognized effect on gravity, caused by the mass of air giving an upward increase in attraction and reducing gravity when air pressure increases, and the opposite (and smaller) effect of surface downward bulging causing an increase in gravity. The resultant gradient will depend on crustal properties, and be between -0.2 and -0.4 µGal/hPa. Assuming a linear relation between air pressure and gravity, the correction due to air pressure, g_{AP}, can be expressed as:

$$g_{AP} = a + bp_{air}$$

The constant b above is the air pressure gravity gradient, with expected value of 0.3 µGal/hPa.

To evaluate result of air pressure correction, other corrections need to be applied as well, including the sensor drift correction. Because the air pressure is slowly changing over days, the drift correction will implicitly also correct for some of the air pressure variations. To try isolating the air pressure effect, a simplified drift correction was applied, as shown in Figure 120. In the following calculations, the air pressure measured at Eelde (Figure 65) is used.

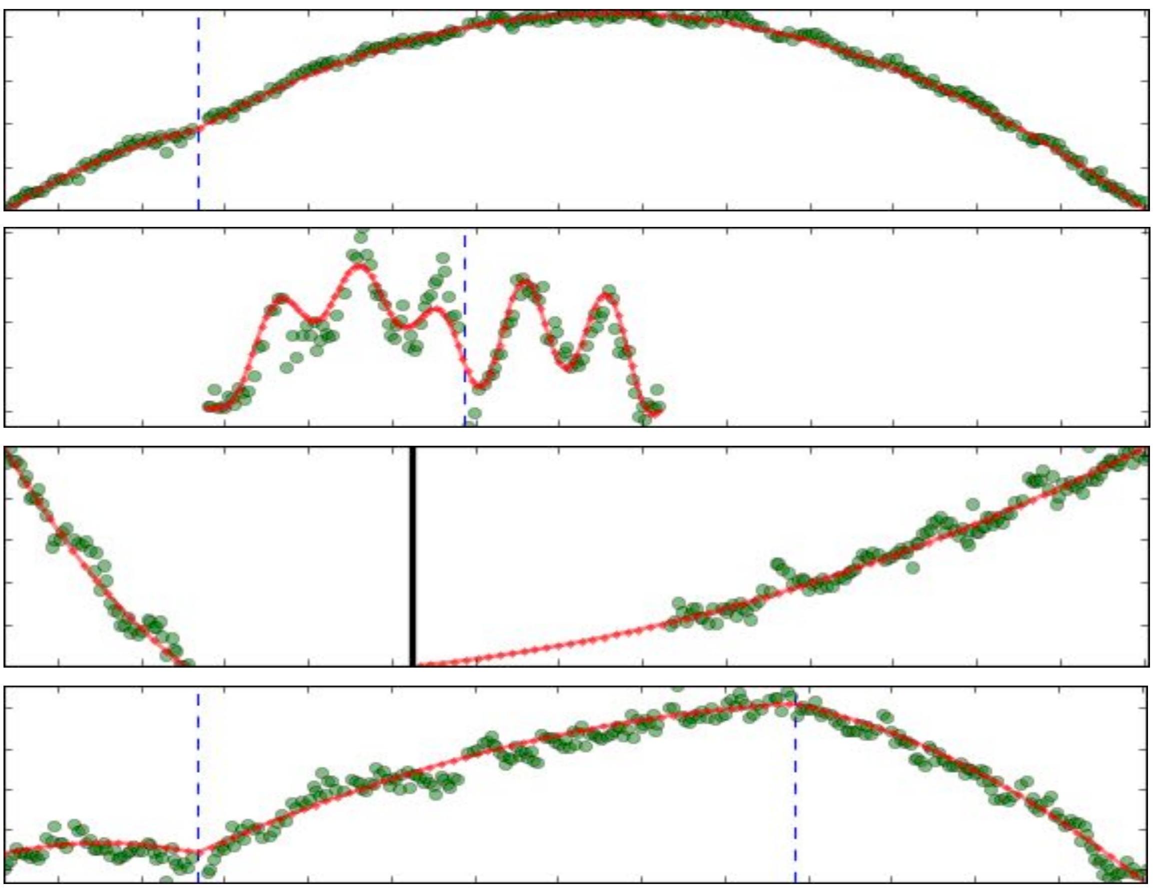

Figure 120: Simplified gravity drift. Green dots are gravity measurement residuals from station means for units 10, 11, 12 and 13 (top to bottom), after linear trend has been removed. Red curves show the drift correction beyond the single linear term. Tares are shown as solid vertical lines and drift segment boundaries without tares as hatched blue vertical lines.

After the other corrections have been applied (drift, solid earth tide, ocean loading etc.), the air pressure may be fitted to the residual with a least square fitting:

$$g_{AP} = a + bp_{air}$$

$$\begin{bmatrix} a \\ b \end{bmatrix} = (A^T A)^{-1} A^T g_{residual}$$

$$A = [1 \quad p_{air}] = \begin{bmatrix} 1 & p_1 \\ 1 & p_2 \\ \vdots & \vdots \\ 1 & p_n \end{bmatrix}$$

where each pressure p_i in p_{air} corresponds to a $g_{residual}$ value (the recorded air pressure is interpolated to match the timestamps of $g_{residual}$). In Figure 121, a slight correlation is seen between gravity residuals and air pressure on units 10 and 13 (where we have full sets of data). Any correlation can not be seen in unit 11 and 12.

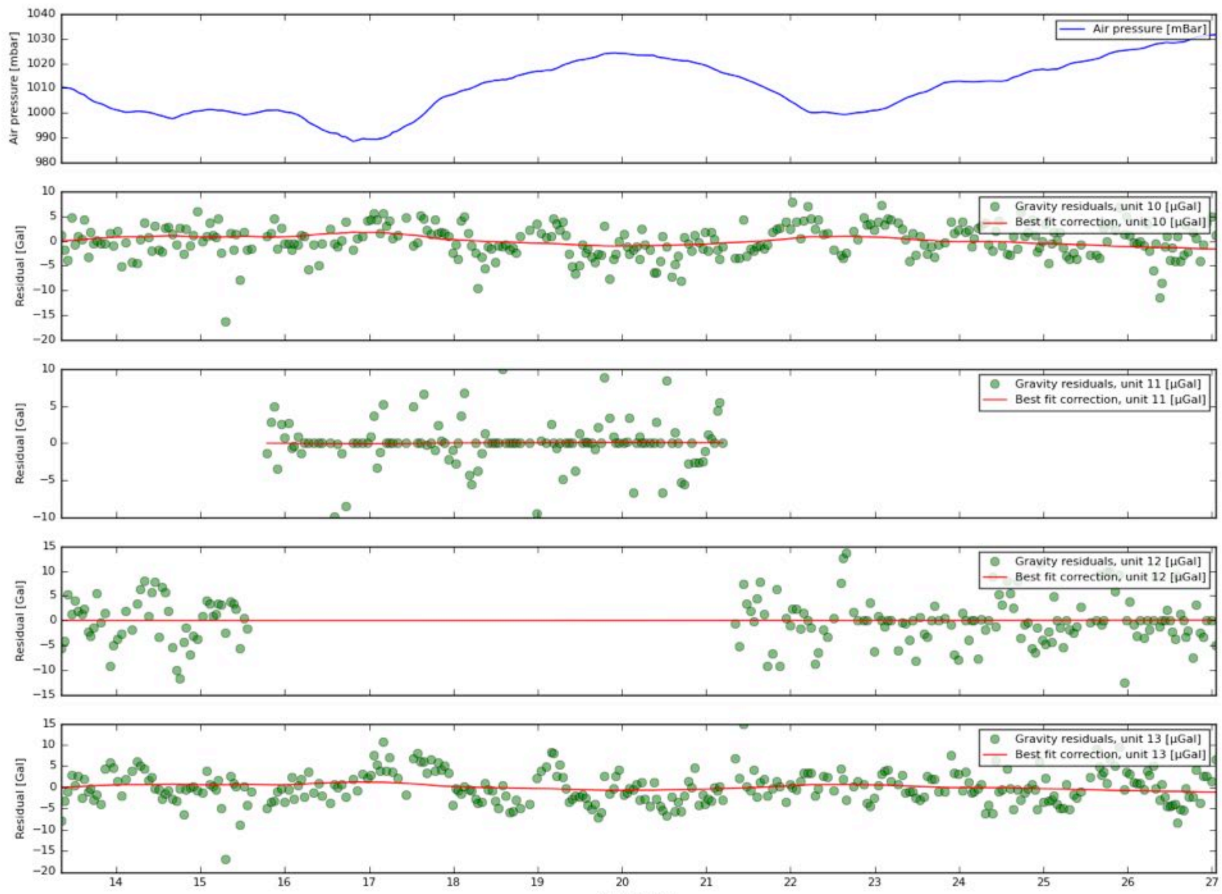

Figure 121: Upper plot: measured air pressure. Lower four plots: Gravity residuals (green dots) and the best fit air pressure correction (red lines), for units 10 to 13. A simple drift model with long intervals has been used.

Linear air pressure corrections have been applied with varying coefficient (air pressure gravity gradients) ranging from -1.0 to 1.0 µGal/hPa. For every gradient, a drift inversion has been performed and the standard deviation of the residuals recorded (Figure 122). Again, improvements by air pressure corrections are seen on units 10 and 13, with optimal gradient (which gives the lowest residuals) at -0.2 and -0.4 µGal/hPa respectively.

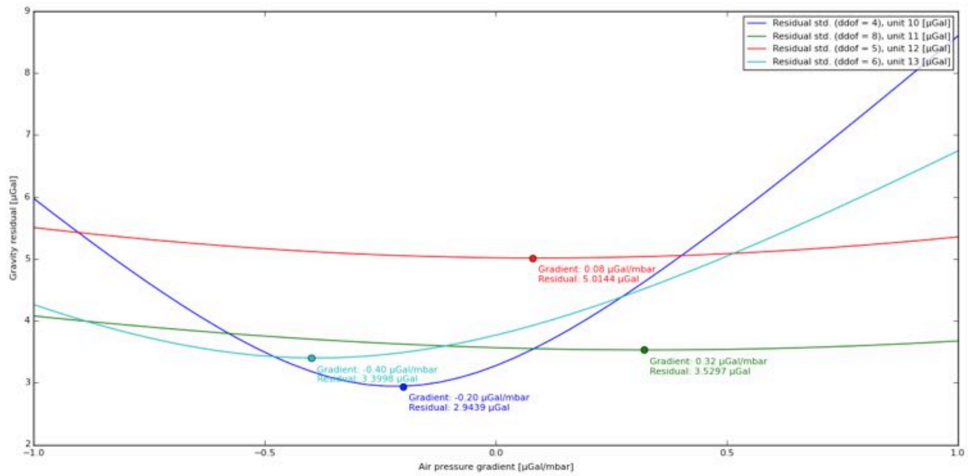

Figure 122: Gravity residual (standard deviation) as function of coefficient applied to air pressure correction.

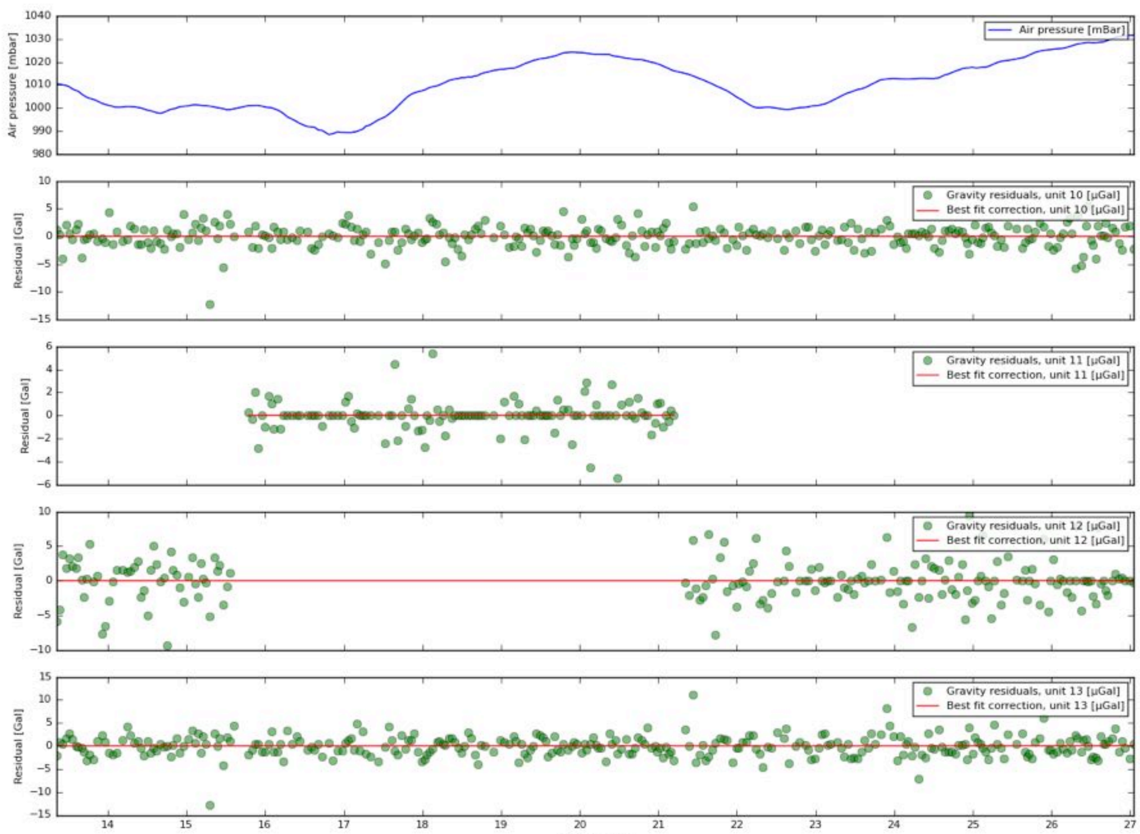

Figure 123: Upper plot: measured air pressure. Lower four plots: Gravity residuals (green dots) and best fit air pressure correction (red lines), for units 10 to 13. A detailed drift model with short intervals has been used.

With the more detailed drift correction applied, as shown in section 13.3, the effect of air pressure is practically invisible (Figure 123), with poorly defined optimal values of the coefficient (Figure 124).

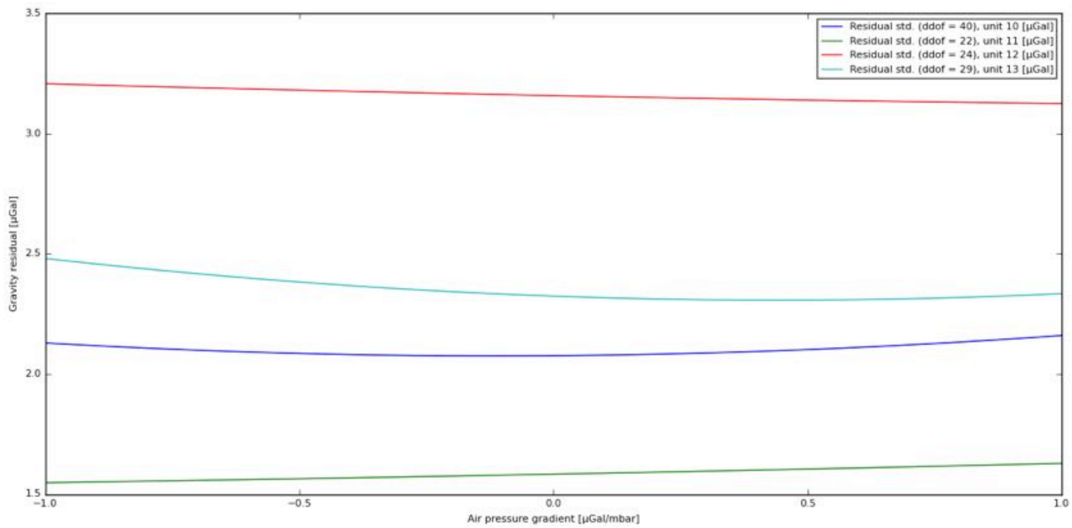

Figure 124: Gravity residual (standard deviation) as function of coefficient applied to air pressure correction.

Finally, we applied the air pressure corrections prior to drift inversion, and evaluated the results. Results are varying for the units, with the measurement repeatability number increasing from 1.60 to 1.72 μGal when applying the -0.3 μGal/hPa gradient. Surprisingly, with positive gradients of 0.2-0.4 μGal/hPa, repeatability improves marginally, from 1.68 to 1.67 μGal. We interpret this as coincidental, caused by a better fit of other parts of the drift. Based on these results, we did not include air pressure correction in the final processing.

14 Reprocessing of 20th century data

The first survey lasted two work weeks, in the autumn of 1978 (Table 1). Reference stations were at #26 Utrecht and #2 Gasselte (Table 2). The second survey (1984) lasted nearly four weeks, in June with numerous measurements at stations outside Groningen. The 1988 and 1996 surveys both took place during two work-weeks, separated by a weekend. Data for the 1978, 1984 and 1988 surveys were available as raw text files with one raw gravity reading and time for each measurement, while the 1996-data files had about two readings for each measurement.

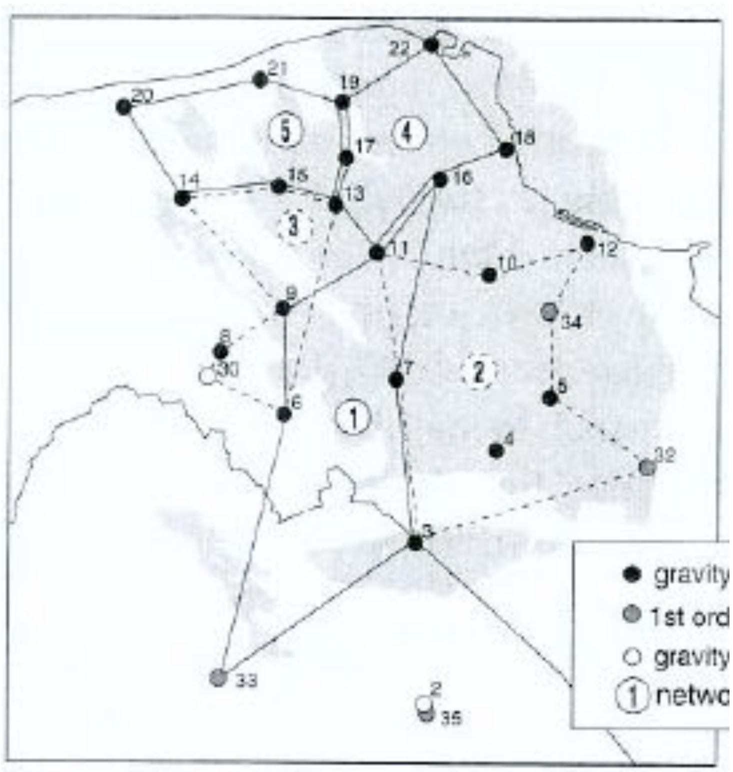

Figure 125: Map of the Groningen field, with stations surveyed in the past.

14.1 1978-survey

In 1978, 113 measurements were carried out during daytime within 12 survey days. Two weekend breaks of 2 ½ days were followed by Mondays of only recording in Utrecht (#26) and Gasselte (#2). Recorded times are assumed to be local, as a shift to UTC gave lower repeatability. In 1978, summer time was used throughout September, and thus 2 hours have been subtracted to get UTC. For October, 1 hour was subtracted to get UTC.

Station #2 Gasselte was used as reference, and each day started and ended with a visit there. Each week started and ended at the Utrecht station (#26), giving 6 measurements at this location. Four of these measurements were the station pair #2 / #26 on a day, and these have been excluded from the further processing, due to possible higher drift uncertainty and little, if any, contribution to the rest of the network. The network of visits is shown in Figure 126.

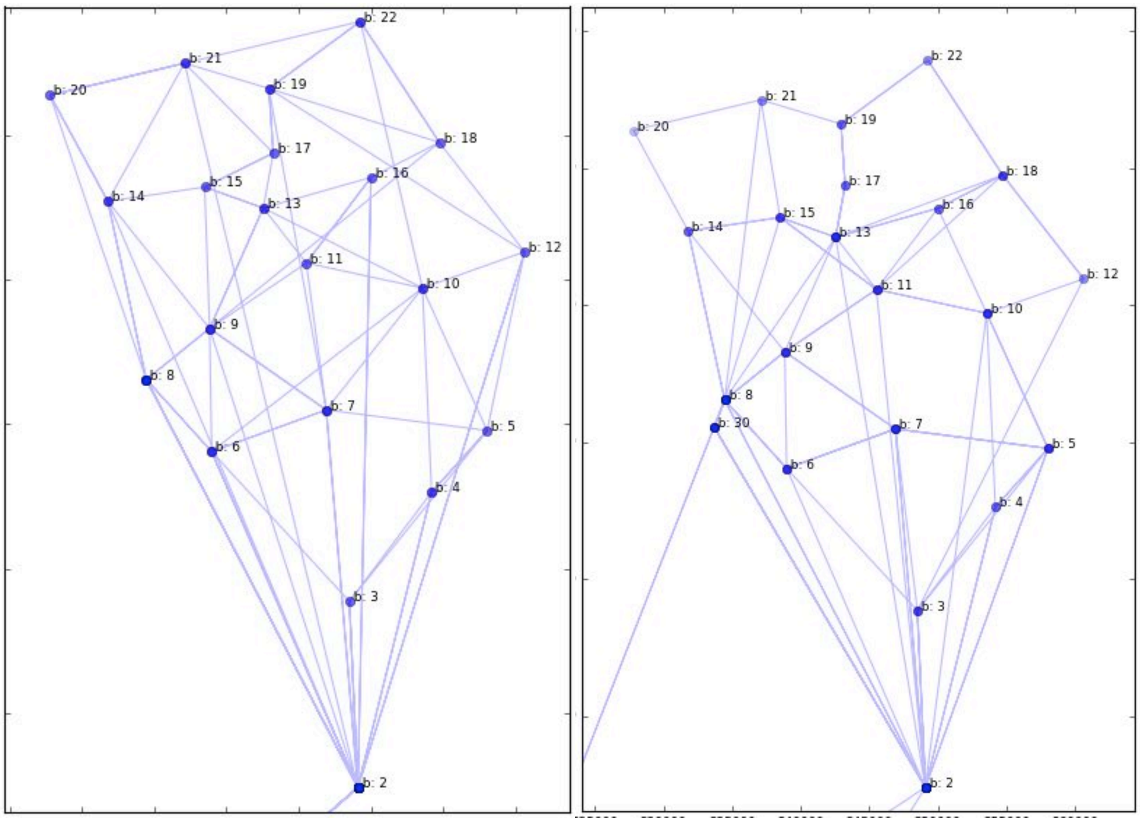

Figure 126: Station network for the 1978 survey (left) and 1984 survey (right).

Input data were supplied by Shell the summer of 2015, in a tabular format, an example of which is shown in Figure 127. In addition to x, y and z-coordinates and local time of each measurement, the reading, tide correction and scale factor corrections (same value of 1.03835 for all measurements) were given.

OBSERVATIONS GRAVITY SURVEY GRONINGEN 1978.

STATION	NR	X	Y	H	LATITUD	LONG.	D	M	YEAR	TIME	Z	JUL.DAY	READING	TIDE	SCALE	INSTR
UTRECHT-HOM.	26	134400.	454840.	0.00	52.0812	5.0874	25	9	1978	1350	2	28788.493	4613.392	-0.034	1.03835	LCR079
GASSELTE	2	249087.	564825.	17.84	53.0618	6.7916	25	9	1978	1820	2	28788.681	4673.313	-0.071	1.03835	LCR079
GASSELTE	2	249087.	564825.	17.84	53.0618	6.7916	26	9	1978	1112	2	28789.383	4673.209	0.020	1.03835	LCR079
TUSSCHENKLAP.	4	254200.	575280.	-0.43	53.1548	6.8711	26	9	1978	1225	2	28789.434	4690.289	0.002	1.03835	LCR079
SCHILDMEER	10	253565.	589435.	-0.85	53.2821	6.8659	26	9	1978	1430	2	28789.521	4700.192	-0.040	1.03835	LCR079
TEN POST	11	245525.	591170.	-0.15	53.2991	6.7458	26	9	1978	1530	2	28789.562	4697.672	-0.058	1.03835	LCR079
STEDUM	13	242555.	594970.	1.18	53.3337	6.7023	26	9	1978	1620	2	28789.597	4699.847	-0.068	1.03835	LCR079
LEERMENS	16	250010.	597095.	1.13	53.3516	6.8149	26	9	1978	1712	2	28789.633	4703.287	-0.074	1.03835	LCR079
GASSELTE	2	249087.	564825.	17.84	53.0618	6.7916	26	9	1978	1857	2	28789.706	4673.307	-0.072	1.03835	LCR079
GASSELTE	2	249087.	564825.	17.84	53.0618	6.7916	27	9	1978	923	2	28790.308	4673.226	0.023	1.03835	LCR079
GASSELTE	2	249087.	564825.	17.84	53.0618	6.7916	27	9	1978	935	2	28790.316	4673.231	0.025	1.03835	LCR079
USQERT	21	237100.	605005.	1.73	53.4248	6.6230	27	9	1978	1140	2	28790.403	4711.083	0.022	1.03835	LCR079
EENRUM	20	227800.	602785.	1.64	53.4062	6.4826	27	9	1978	1300	2	28790.458	4704.983	0.002	1.03835	LCR079

Figure 127: Example of format of input data to the 1978-survey reprocessing.

In the reprocessing, the given tide correction was replaced with QuadPro's calculation, which deviated by up to 5 µGal. This improved repeatability slightly. The given scale factor was applied to the data.

A drift solution with one linear interval each day and allowing for a jump (tare) between the days was used. The drift segments as deviations from one linear drift are shown in Figure 128. The overnight jumps are up to nearly 20 µGal. Best fit drift rates change by up to +/- 15 µGal/day. Measurements

#65 and 66, at station 12 and 2, deviate strongly from the rest of the measurements that day. They could have been edited out of the processing, but we inserted a tare just before them – of size about 45 μGal.

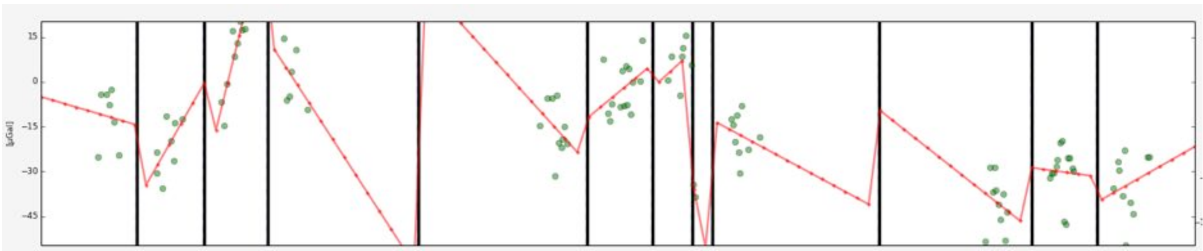

Figure 128: Drift segments and drift solution for the 1978 data. Green dots are gravity measurement residuals from station means after linear trend has been removed. X-axis is survey time. Red curves show the drift correction beyond one linear term. Tares are shown as solid vertical lines.

Resulting repeatability; deviation from station means, is 10.0 μGal when the degrees of freedom are taken into account (Table 48). The distribution of deviations is close to normal, with no strong outliers. Average station uncertainty is 5.2 μGal (Figure 130).

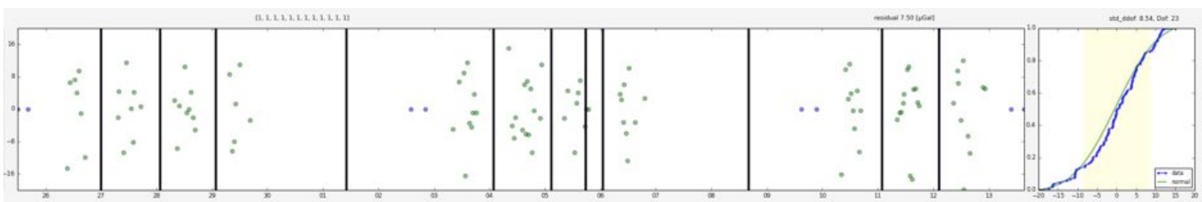

Figure 129: Measurement residuals after drift corrections have been applied to the 1978-data; that is the difference between the red line and the green dots in Figure 128.

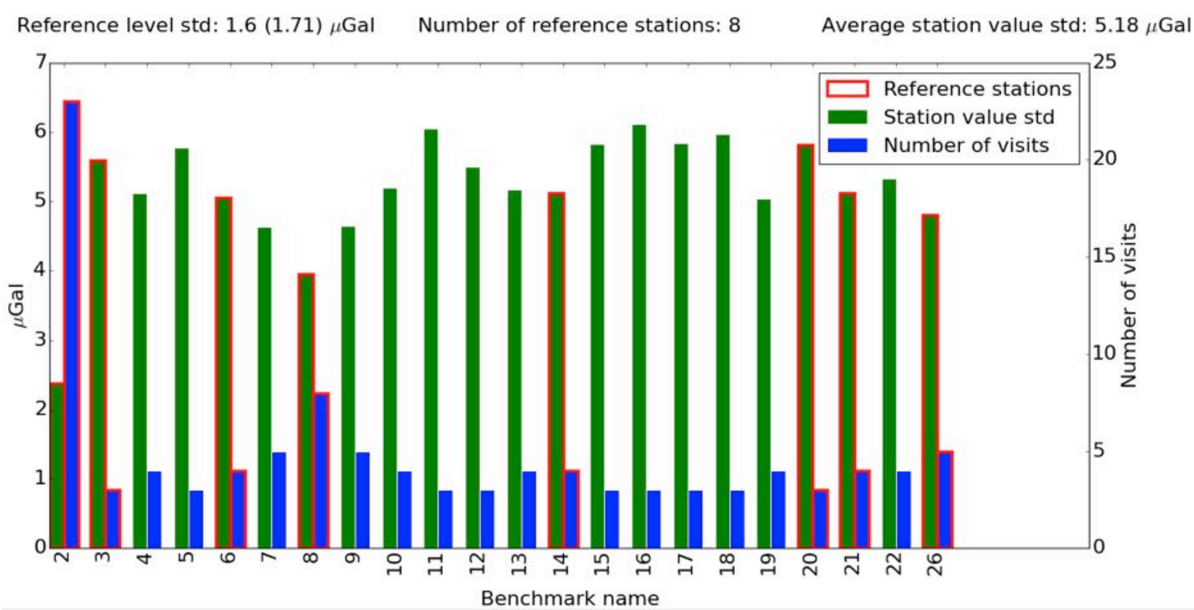

Figure 130: Station uncertainties for the 1978-survey.

14.2 1984-survey

In the 1984-survey, several measurements were done at stations further south in the Netherlands. The 3 first measurements were done at #1 Pijnacker (near Delft). These are single measurements on separate days, and they are of little value. The first measurement of any use was done June 12th, connecting #26 Utrecht with #2 Gasselte. After the week-end break June 23rd-24th, measurements started at #1, followed by #26 and #2, giving another valid tie to the Groningen network. On June 28th, #2 was measured together with #30, #29, #27 and #26, giving the 3rd tie to the greater Dutch network. The last 20 measurements were all at that larger, southern network. The network of visits is shown in Figure 126.

The data format was similar to 1978 (Figure 127), except that the scale factor was 1.06705. Times were shifted 2 hours back, to align with UTC. The survey spanned nearly a month, with three weekend breaks.

Measurement #9 and #10 at station 8, which has been measured 11 times, are deviating with nearly 40 µGal and >20 µGal. They have been edited out. Likewisehas measurement #11 at station 9, as it shows a deviation of about 25 µGal from the average of 5 visits. The subsequent measurements, #12 and #13, show deviations of more than 10 µGal, and have been edited out as well. This may have been a period of unstable measurements.

A drift solution with one linear interval each day separated by tares, was used, as shown in Figure 131. During the second week, the overnight jumps are up to about 15 µGal, and the daytime drift is about 15 µGal/day higher than the survey-long average. A large (>150 µGal) jump in the drift curve occurred between June 26th and 27th. We have no explanation for this, and no information on whether some operational or environmental changes caused the jump.

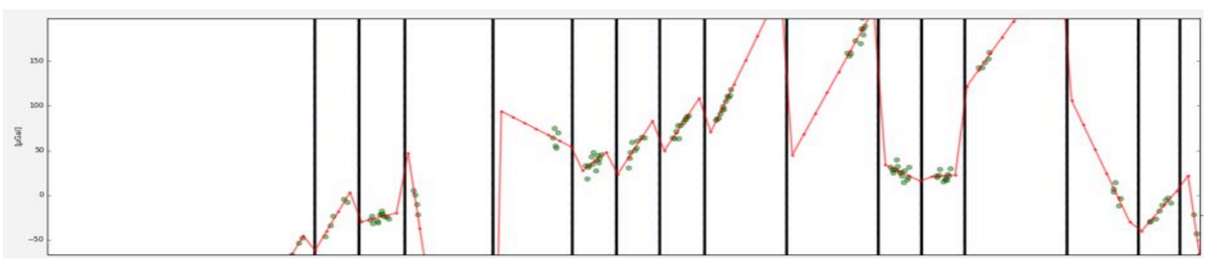

Figure 131: Drift segments and drift solution for the 1984 data. Green dots are gravity measurement residuals from station means after linear trend has been removed. X-axis is survey time. Red curves show the drift correction beyond one linear term. Tares are shown as solid vertical lines.

After editing out the above stations, as well as measurement #58 at station 10, which is a 22 µGal – 3σ-outlier, we obtain the repeatability (deviation from stations means) of 5.7 µGal, as shown in Figure 132. The distribution is close to normal. Average station uncertainty is 3.4 µGal (Figure 133).

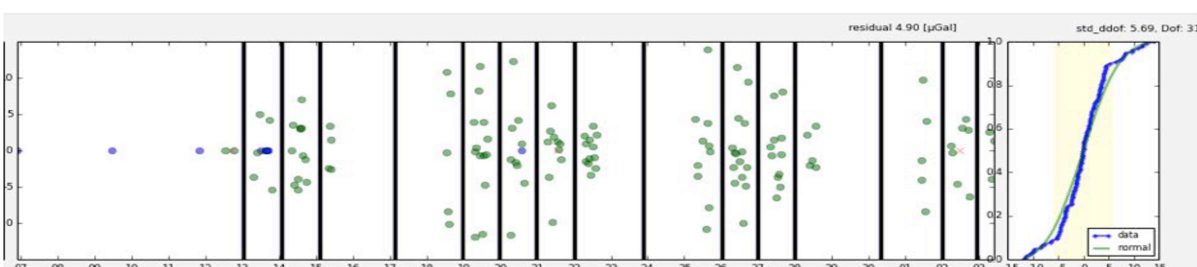

Figure 132: Measurement residuals after drift corrections have been applied to the 1984-data; that is the difference between the red line and the green dots in Figure 131.

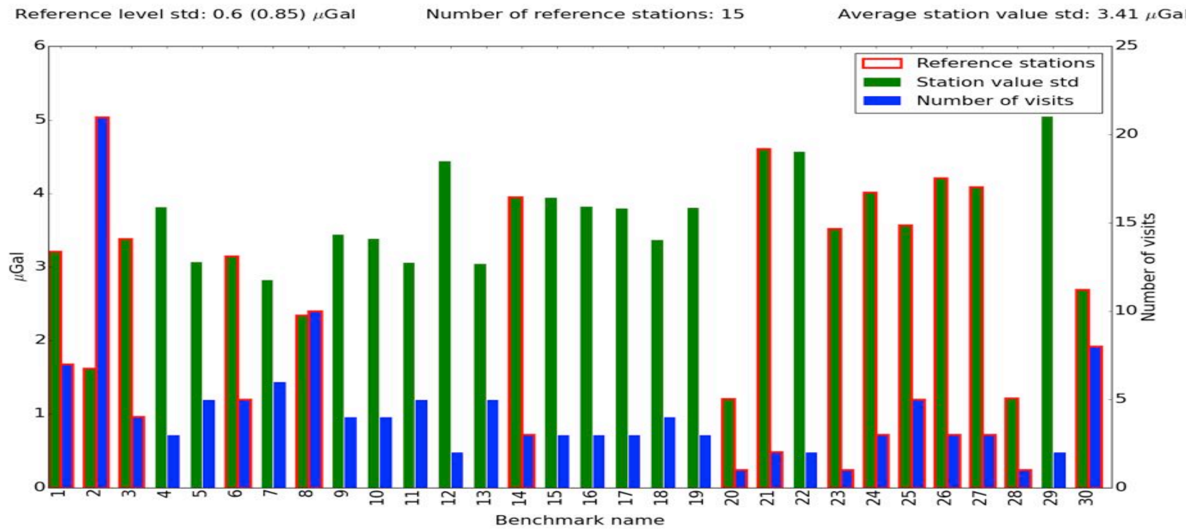

Figure 133: Station uncertainties for the 1984-data.

14.3 1988-survey

Measurements were done in two periods of 4 days, with a 3 ½ days gap between. The Groningen network was tied to station #29 Zwolle at the beginning and end of each 4-days period. The network of visits is shown in Figure 134.

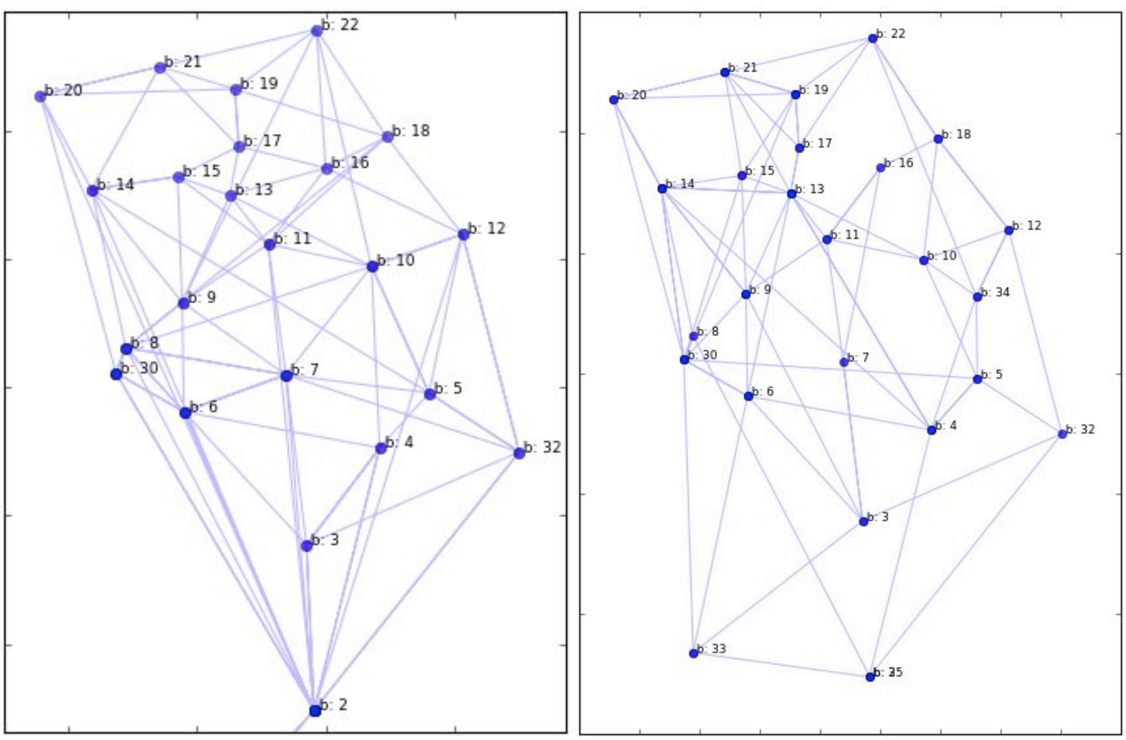

Figure 134: Station network for the 1988 survey (left) and 1996-survey (right).

Data format was similar to 1978 (Figure 127), except that the scale factor was 1.022. Times were shifted 2 hours backwards, to UTC.

A fairly simple drift solution is sufficient for the data correction; daily segments with tares between. For June 6th, 7th and the first part of 8th, one continuous 2. order drift segment was sufficient (Figure 135. On June 8th, just after noon, a jump of about 40 μGal occur. A 2nd order segment was assigned to the third day as well, giving slightly better repeatability.

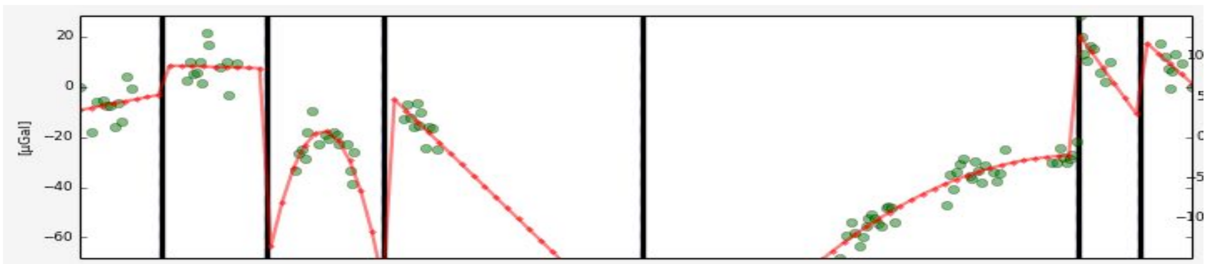

Figure 135: Drift segments and drift solution for the 1988 data. Green dots are gravity measurement residuals from station means after linear trend has been removed. X-axis is survey time. Red curves show the drift correction beyond one linear term. Tares are shown as solid vertical lines.

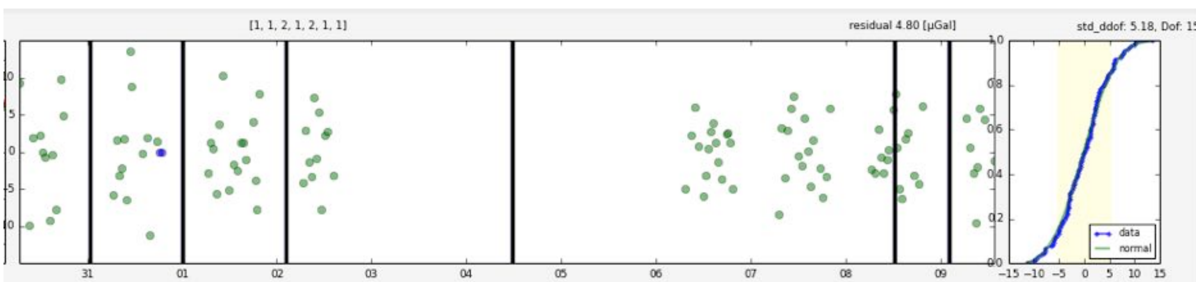

Figure 136: Measurement residuals after drift corrections have been applied to the 1988-data; that is the difference between the red line and the green dots in Figure 135.

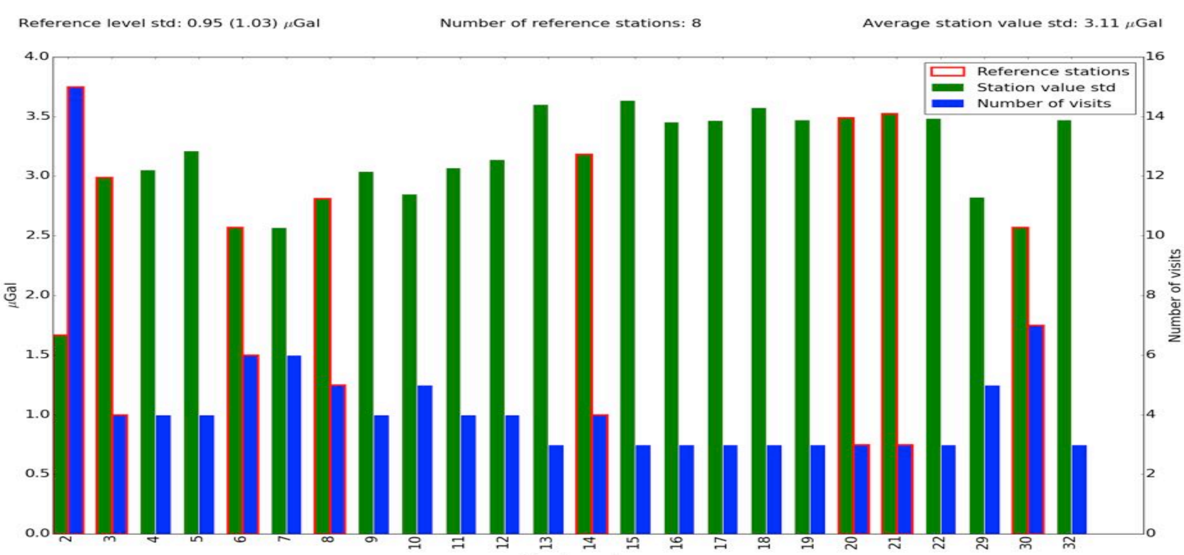

Figure 137: Station uncertainties for the 1988-data.

14.4 1996-survey

The survey was done during two work weeks; 5 consecutive days with a 2 ½ days weekend between. No ties to stations outside the field was done. Two gravimeters were recorded, sequentially at each site.

The data format is different from the older surveys. Two to three readings were made for each measurement at a station with each sensor. An example of the format used in the supplied files is shown in Figure 138. We assume that each data line contains the reading (l_j), the feedback reading (f_j) and the time in hour and minutes (hhmm). Times were shifted 1 hour back (from European wintertime to UTC).

```
06 02 96
1
      6
lcrg785a
4813813    -30  938
4813780      2  941
  0.000

06 02 96
1
      9
lcrg785a
4819907     43 1027
4819961    -10 1030
  0.000

06 02 96
1
     11
lcrg785a
4823812     28 1101
4823857    -18 1104
4823835      4 1108
  0.000
```

Figure 138: Format of the 1996-data files supplied to the reprocessing.

The readings were converted to gravity using the formula from Bilker (1996):

$$gr_j = l_j + f_j \cdot s_{f1} + f_j^2 \cdot s_{f2}$$

where:

- gr_j is the corrected observation
- l_j is the reading from the gravimeter
- f_j is the reading from the feedback-system
- s_{f1} is the linear correction coefficient
- s_{f2} is the quadratic correction coefficient

The coefficients s_{f1} and s_{f2} were found by optimizing repeatability. They can be compared to those used in Bilker (1996) in Table 46.

		s_{f1}	s_{f2}
G785	This study	0.94	0.0047
	Bilker (1996)	1.001001	0.000227
G971	This study	0.999	-0.0035
	Bilker (1996)	0.999885	-0.000143

Table 46: Feedback coefficients.

The standard deviation of the 2-3 readings at each measurement is 3.2 µGal for G785 and 2.7 µGal for G971. The standard deviations do not show any correlation with residuals after drift correction, as seen in Figure 139. Neither do residuals correlate with the recovery calculated from the readings of each measurement, as seen in Figure 140. The average recovery is 2.6 nGal/s for G785 and -3.4 nGal/s for G971.

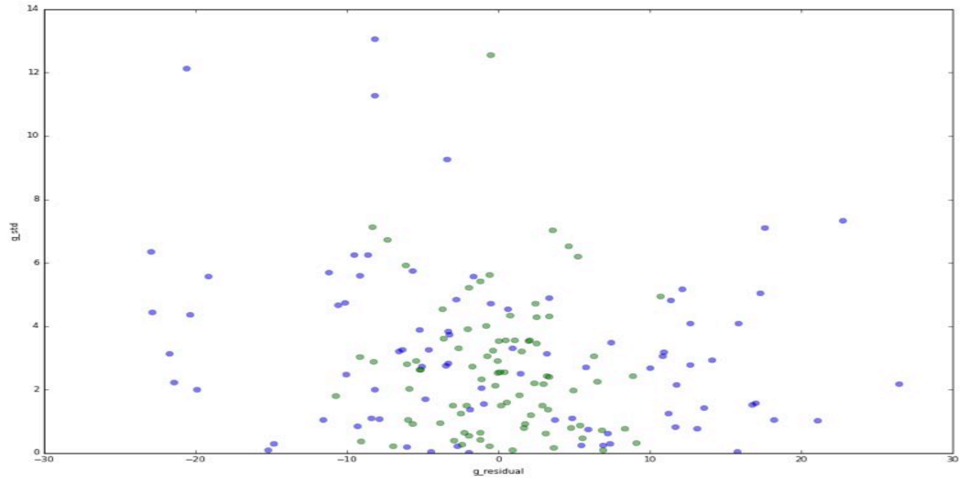

Figure 139: Cross-plot of standard deviation of readings within a measurement and the residual after drift correction. Blue dots are G785 and green dots are G971.

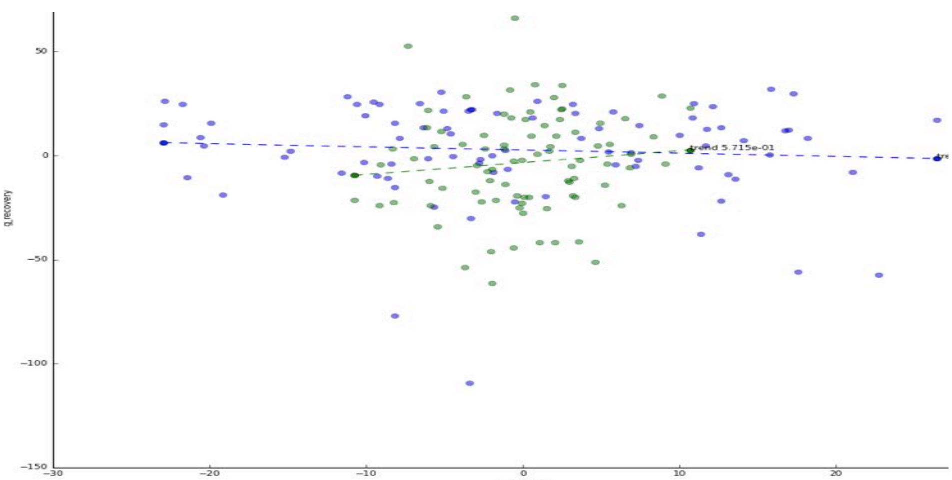

Figure 140: Cross-pot of recovery of readings within a measurement and the residual after drift correction. Blue dots are G785 and green dots are G971.

Unit differences are cross-plotted with gravity (relative to an arbitrary zero level) in Figure 141. There is some correlation. Scale factor adjustments relative between the units, different for positive and negative g values, would remove the trend and lower the RMS of the difference, which is 17 μGal. However, as we don't have a physical explanation for this, no correction has been applied.

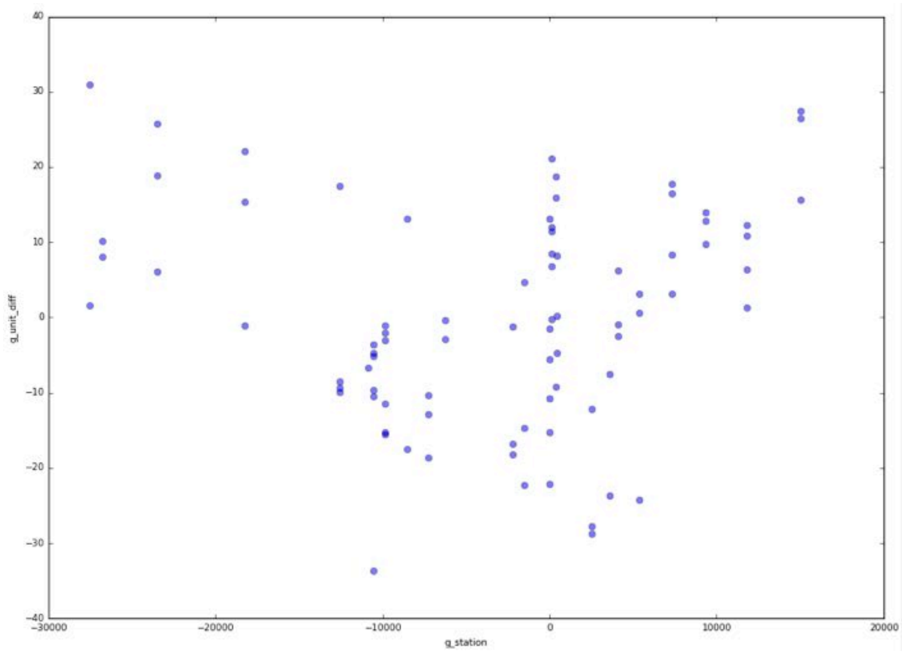

Figure 141: Unit difference as function of gravity.

A linear drift correction was applied to each day, and one jump (tare) was allowed for at every night. Three measurements were removed for G785 and 1 removed for G971. The resulting drift segments are shown in Figure 142, and the residuals in Figure 143. The residuals are close to a normally distributed. All drift corrections are shown in Figure 144. For G971 there is a clear pattern of higher drift during the measurement periods than in between. When individual drift corrections are applied to each unit, G971 has a standard deviation of 5.6 μGal and G785 a standard deviation of 10.1 μGal. For joint drift inversion of the two units, with G971 given 4 times more weight, unit repeatabilities are 5.7 and 15.0 μGal, respectively. Measurement repeatability is 5.0 μGal (Figure 145). Average station uncertainty is 5.4 μGal (Figure 146).

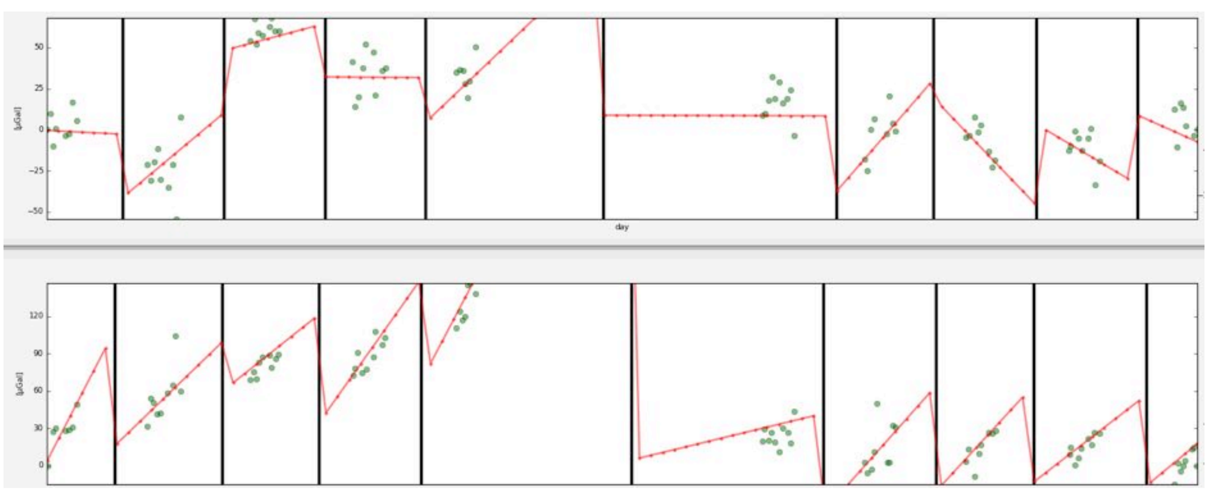

Figure 142: Drift segments and drift solution for G785 (upper) and G971 (lower) in 1996. Green dots are gravity measurement residuals from station means after linear trend has been removed. X-axis is survey time. Red curves show the drift correction beyond one linear term. Tares are shown as solid vertical lines.

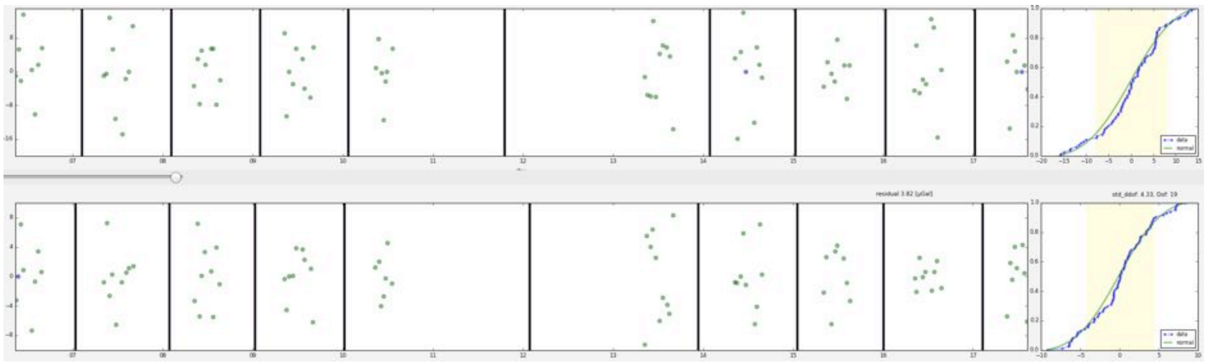

Figure 143: Measurement residuals after drift corrections have been applied to G785 (above) and G971 (below) in 1996; that is the difference between the red line and the green dots in Figure 142.

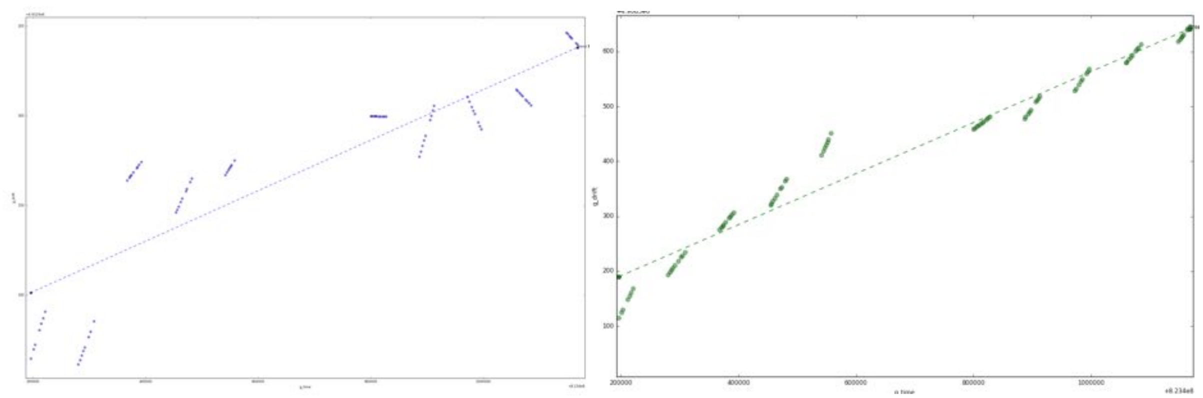

Figure 144: All drift corrections, including the linear, for G785 (left) and G971 (right).

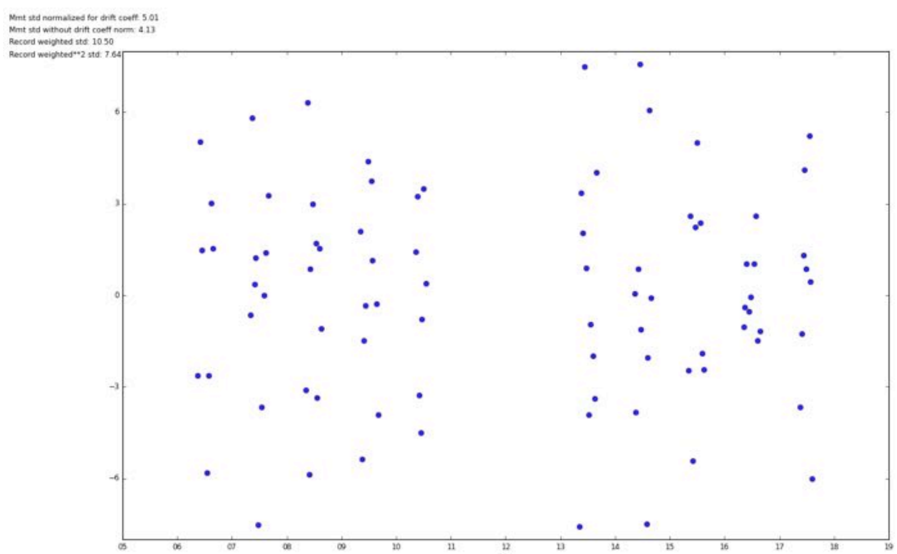

Figure 145: Repeatability of each measurement after joint drift inversion.

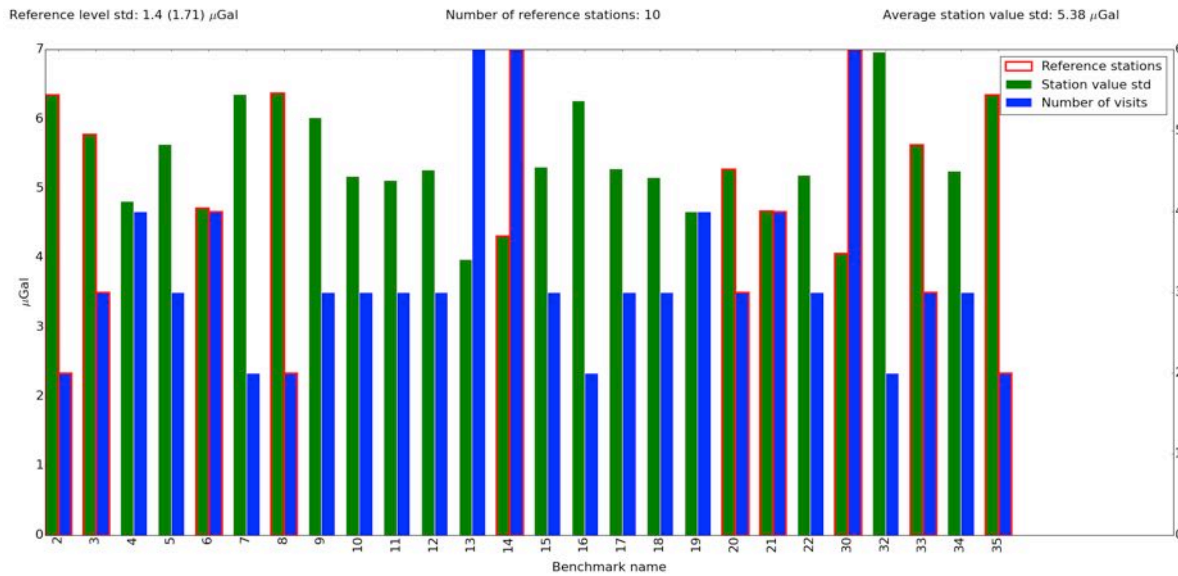

Figure 146: Station uncertainties for the 1996-data.

14.5 Tide corrections in past surveys

Earth tides can have peak-to-peak amplitudes up to 200 µGal. During the 2015-survey, the peak-to-peak amplitudes were up to about 160 µGal (Figure 147), with a dominant half-day period in the start and end of the period, and a daily period in the middle. Differences across the field were up to +/- 1 µGal (Figure 147).

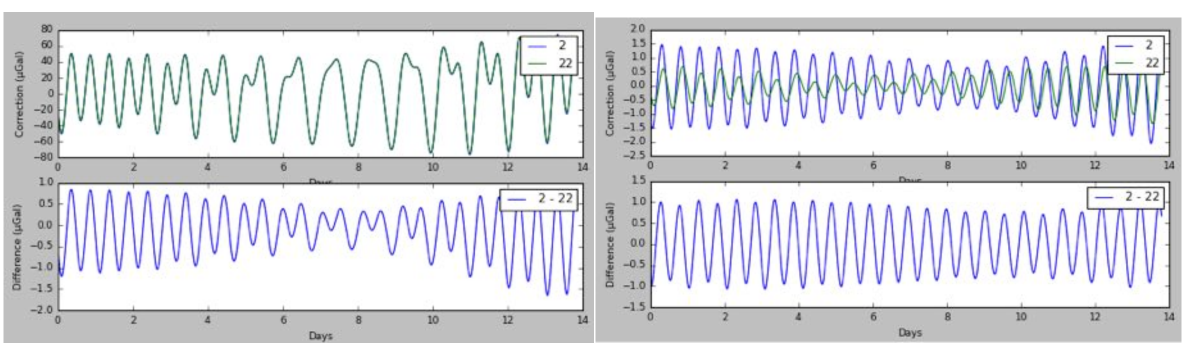

Figure 147: Modeled earth tide (left) and ocean loading (right) during the 2015-survey, for stations 2 and 22 (above) and their difference (below).

Values of earth tides were given in the files we received. We tested using these values for correction as opposed to QuadPro's updated earth tide correction. The standard deviation of residuals after drift inversion with different tide corrections are shown in Table 47. The QuadPro model gives somewhat better results than correcting with the earth tide values supplied with the data files. Ocean loading improves the 1984-data slightly, but is insignificant for the other vintages. The QuadPro model including ocean loading was used in the re-processing of all vintages.

Survey	Original gravtide	Original gravtide + ocean loading	QuadPro gravtide	QuadPro gravtide + ocean loading
1978	9.15	7.25	9.04	9.03
1984	9.51	9.55	9.21	9.11
1988	7.36	7.40	7.14	7.16
1996 G971			5.27	5.29

Table 47: Standard deviation of residuals after different tide corrections have been applied. All values are in µGal.

14.6 Survey statistics

Key statistics for the surveys are shown in Table 48.

<table>
<tr><th>Year</th><th>Sensor</th><th>Number of measure-ments</th><th>Number of invalid measure-ments</th><th>Number of invalid measure-ments at Groningen</th><th>Number of measure-ments per drift coefficient</th><th>Unit standard deviation</th><th>Unit weight</th><th>Measure-ment repeata-bility</th><th>Station value uncertainty (average standard deviation)</th><th>Peak-to-peak scatter</th><th>Station value uncertainty (average standard deviation) from van Gelderen et al 1999</th></tr>
<tr><td>1978</td><td>G79</td><td>113</td><td>8</td><td>0</td><td>4.7</td><td>10.0</td><td>1</td><td>10.0</td><td>5.2</td><td>35</td><td>6-7</td></tr>
<tr><td>1984</td><td>G258</td><td>140</td><td>9</td><td>6</td><td>4.4</td><td>6.7</td><td>1</td><td>6.7</td><td>3.4</td><td>25</td><td>6-7</td></tr>
<tr><td>1988</td><td>G785</td><td>109</td><td>2</td><td>2</td><td>6.8</td><td>6.0</td><td>1</td><td>6.0</td><td>3.1</td><td>25</td><td>4-5</td></tr>
<tr><td rowspan="2">1996</td><td>G785-103</td><td rowspan="2">114</td><td>1</td><td>1</td><td>4.3</td><td>15.0</td><td>0.25</td><td rowspan="2">5.0</td><td rowspan="2">4.3</td><td>50</td><td rowspan="2">4-5</td></tr>
<tr><td>G971-104</td><td>1</td><td>1</td><td>4.3</td><td>5.7</td><td>1.0</td><td>22</td></tr>
<tr><td rowspan="4">2015</td><td>10</td><td>309</td><td>3</td><td>3</td><td>12.4</td><td>3.0</td><td>0.8</td><td rowspan="4">1.7</td><td rowspan="4">1.2</td><td>16</td><td></td></tr>
<tr><td>11</td><td>124</td><td>21</td><td>21</td><td>9.5</td><td>4.7</td><td>0.2</td><td>24</td><td></td></tr>
<tr><td>12</td><td>184</td><td>15</td><td>15</td><td>10.2</td><td>3.0</td><td>0.4</td><td>15</td><td></td></tr>
<tr><td>13</td><td>309</td><td>4</td><td>4</td><td>12.4</td><td>2.5</td><td>1.0</td><td>12</td><td></td></tr>
</table>

Table 48: Survey repeatabilities for the Groningen surveys. All gravity uncertainties are in µGal.

15 Hydrology corrections

The central part of the survey area is below sea level; elevations range from -1 m to +3 m (Figure 148, Figure 149). An exception is #2 Gasselte, which is inland of the survey area and has an altitude of 17 m. A large number of canals and dikes criss-cross the survey area, and the water level is controlled by pump stations. Most of the excess water is pumped into the Eemskanaal, from where the water can flow out freely when the gate opens at low tides. The water level in the canals is controlled by a system of automatic pumps. The level is usually ½ to 1 m lower in the winter than in the summer. Much of the area is less than 100 m away from an open dike, and thus the water level in these are highly correlated with the ground water level.

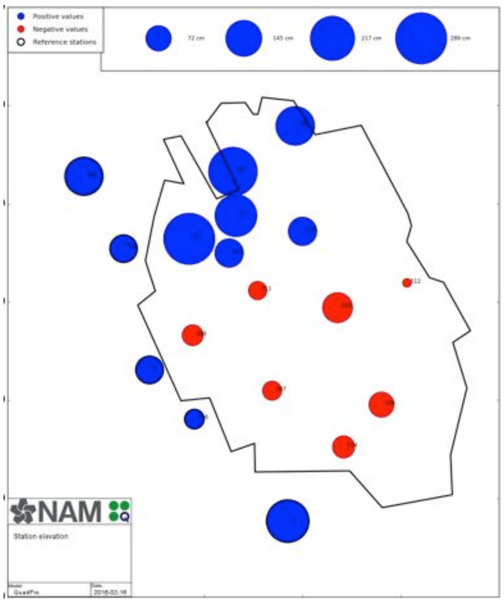

Figure 148: Elevation of 4D stations, except #2/35 Gasselte and #32 Assen. Blue is above NAP, red is below NAP.

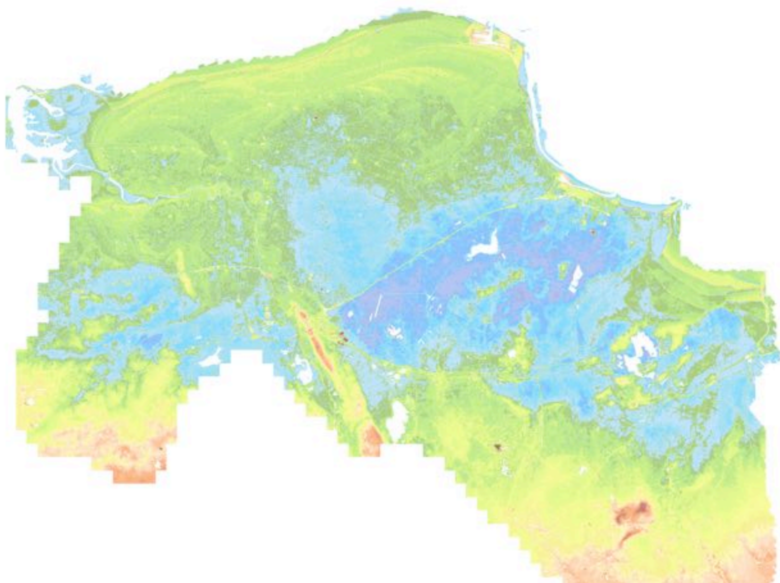

Figure 149: Topography map, from http://kaarten.provinciegroningen.nl/viewer/app/landschap. Blue and violet colors are low land.

A fluctuation in the ground water level of 1 m, may be equivalent to up to 30 cm of water (30% porosity and 100% water saturation – giving a yield of 0.3) and a gravity change of 12 μGal. Hence a significant, but not dominating correction.

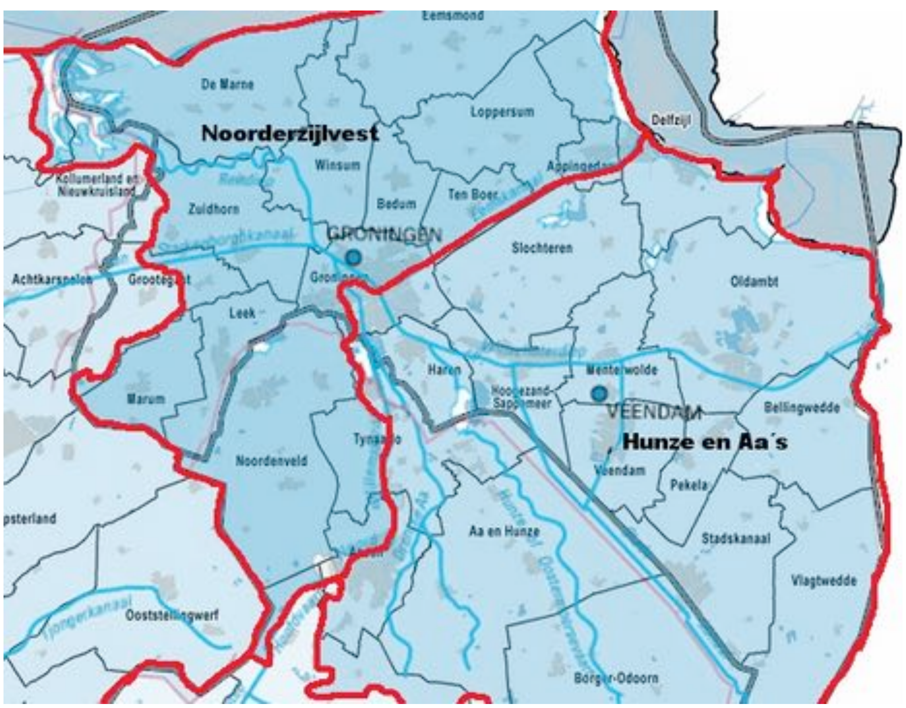

Figure 150: Areal responsibility of the two watershap's covering the survey area.

Data on water level at pump stations and ground water at a few selected locations are available from the watershaps Noorderzijlvest (https://www.noorderzijlvest.nl/) and Hunze en Aa's (http://www.hunzeenaas.nl). These organizations are responsible for controlling the water in the areas shown in Figure 150. A national database of measured ground water levels in the Netherlands, DINOloket (https://www.dinoloket.nl), is an open data portal of the Geological Survey of the Netherlands which is going back several decades. A topographic atlas is available in printed scale 1:25 000 (Termeulen 2014), and a printed atlas of the water ways in scale 1:50 000 (ANWB Wateratlas 2014).

15.1 Water management

The Noorderzijlvest area can be subdivided as shown in Figure 151. Water level is recorded at the stations shown with symbols on the map, and water is discharged to the sea at four places, shown with black arrows. The six areas of Electraboezem (labelled with ELB in the map) always have the same target level of -0.93 m NAP. The three areas in the northeast, Fivelingo, Spijksterpompen and Eemshaven, have a higher summer level and a lower winter level. These are shown in Figure 152. Water level decisions are normally valid for 10 years.

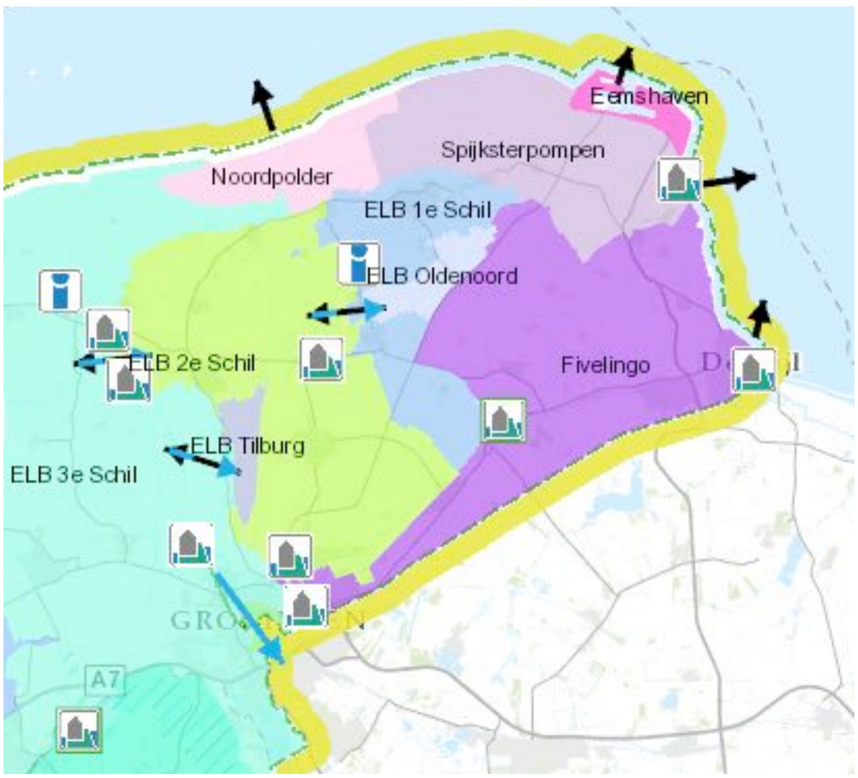

Figure 151: Map of the Noorderzijlvest water management. From https://geo.noorderzijlvest.nl/viewer/index.html?webmap=493a84a5e14a49ada4b2ce9176c020d1.

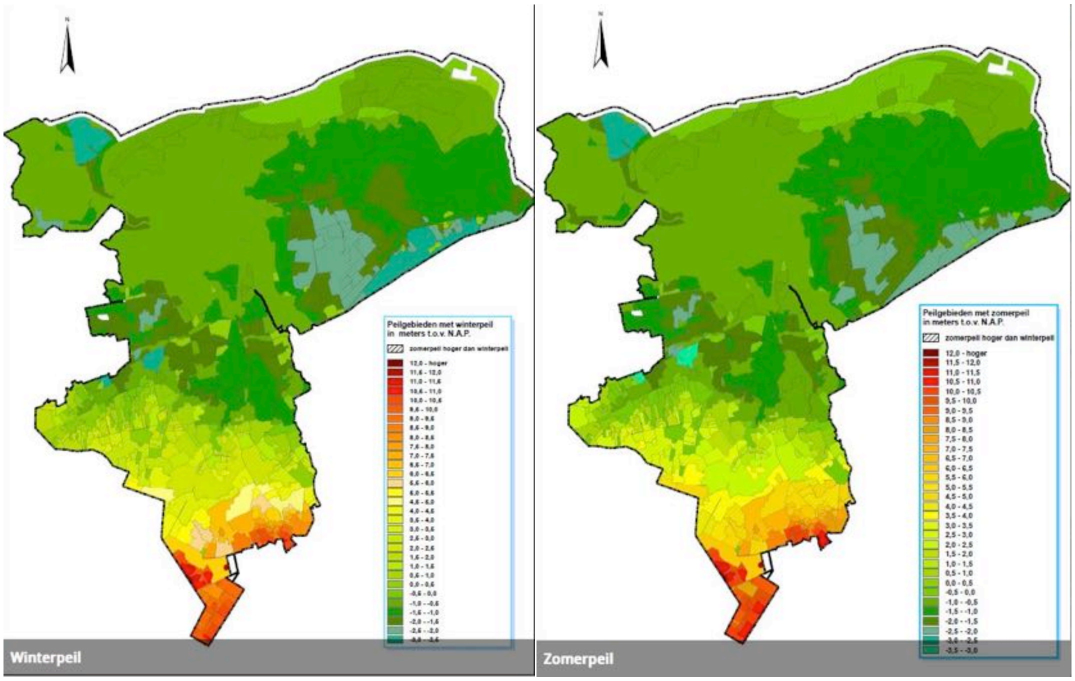

Figure 152: Water level as decided in the Noorderzijlvest area in the winter (left) and summer (right), relative to NAP. From www.noorderzijlvest.nl.

The Hunze en Aa's area is divided into the areas shown in Figure 153, of which the three northernmost + the northern parts of Hunze, Veenkoloniën and Westerwolde have gravity stations. The area has 28 km of seawalls and 3525 km of canals and ditches.

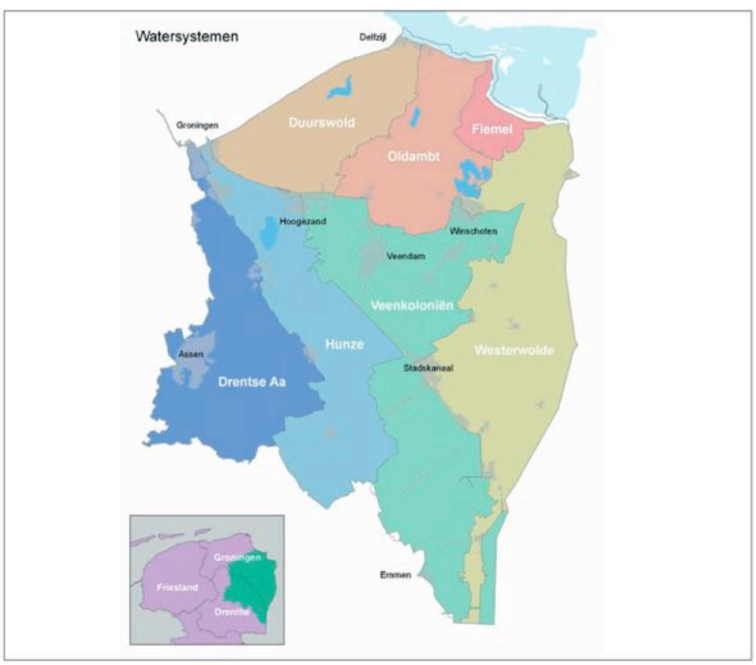

Figure 153: Map of the Hunze en Aa's water management areas. From Hunze en Aa's Beheerplan 2010-2015.

Surface subsidence caused by gas extraction in the Groningen and neighboring gas fields (Figure 154) influences the water management. Salt extraction northwest of Veendam and near Winschoten also cause subsidence and influence the water level. Some subsidence is also caused by peat oxidation of the shallow subsurface (Figure 154, right side).

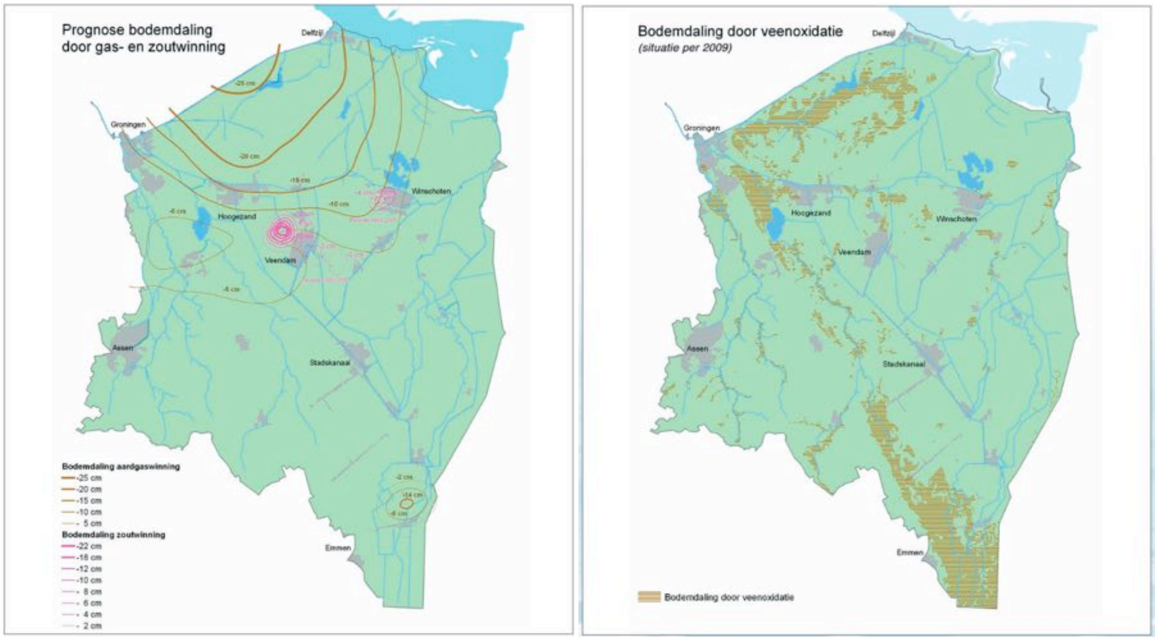

Figure 154: Left: Prognosis for subsidence due to gas- and salt-production. Right: Areas of subsidence due to peat oxidation (per 2009). From Beheersplan 2010-2015.

The highest and lowest average groundwater level relative to the surface is shown in Figure 155. The water is particularly close to the soil surface around Schildmeer and southeast of Groningen, near gravity stations #6 and #10.

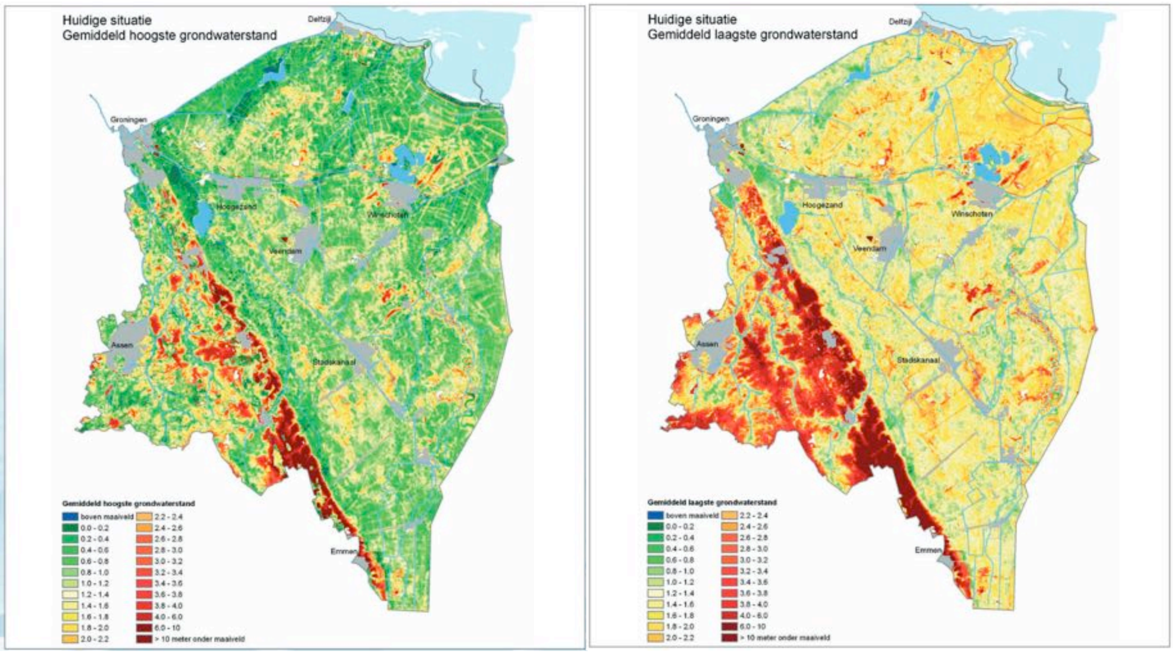

Figure 155: Left: average highest groundwater, Right: average lowest groundwater. All numbers are referred to the surface. From Beheersplan 2010-2015.

15.2 Water level in the canals September 2015

Waterschap Hunze & Aas recorded water level at six locations during the 2015 gravity survey.

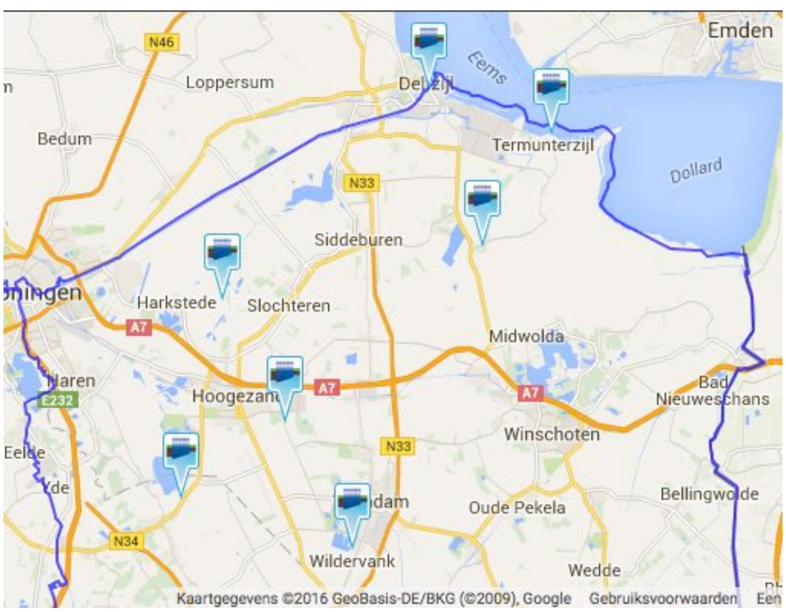

Figure 156: Water level measurement stations run by Waterschap Hunze & Aas.

At Oude Zeesluis, (Old Sea Lock) in Delfzijl, water is discharged into the Ems - Dollard bay. Water from west of Zuidbroek, the Drentsche Aa, the Hunze, the Zuidlaardermeer, Winschoterdiep and the Ems Canal are included in the discharge. When the tide is low, the lock opens to the sea. Rates can reach an average of 80 m^3 per second. Figure 157 shows the water level of the Ems Canal. The target level is 0.57 m NAP, and the level was mostly fluctuating within +/- 0.1 m of that.

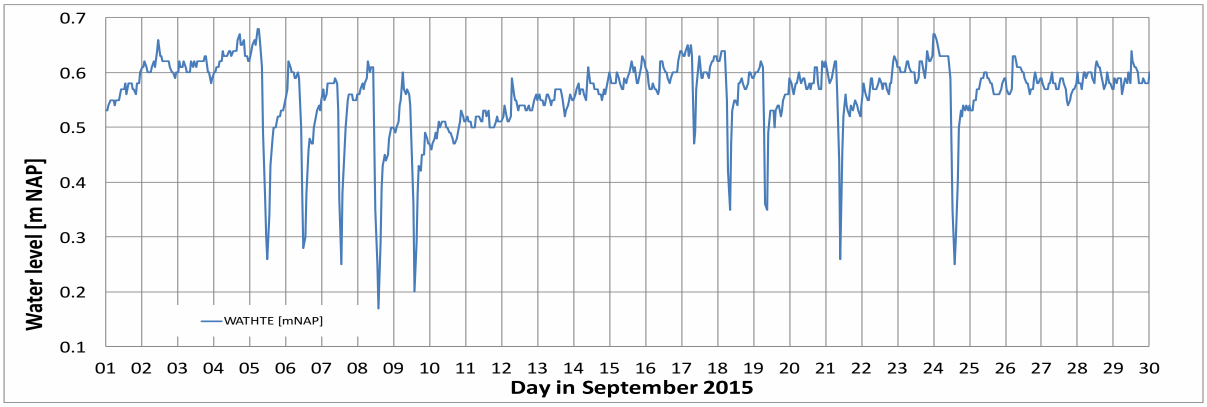

Figure 157: Water level at Oude Zeesluis, Ems Canal side.

The water level in the Termunterzijldiep is measured at Scheve Klap, near Nieuwolda. The Termunterzijldiep is part of the Oldambt Bosom with a fixed target level of -1.36 m NAP. Through the pumping station Rozema at Termunterzijl, water is discharged to the Ems. Figure 158 presents the measured water level.

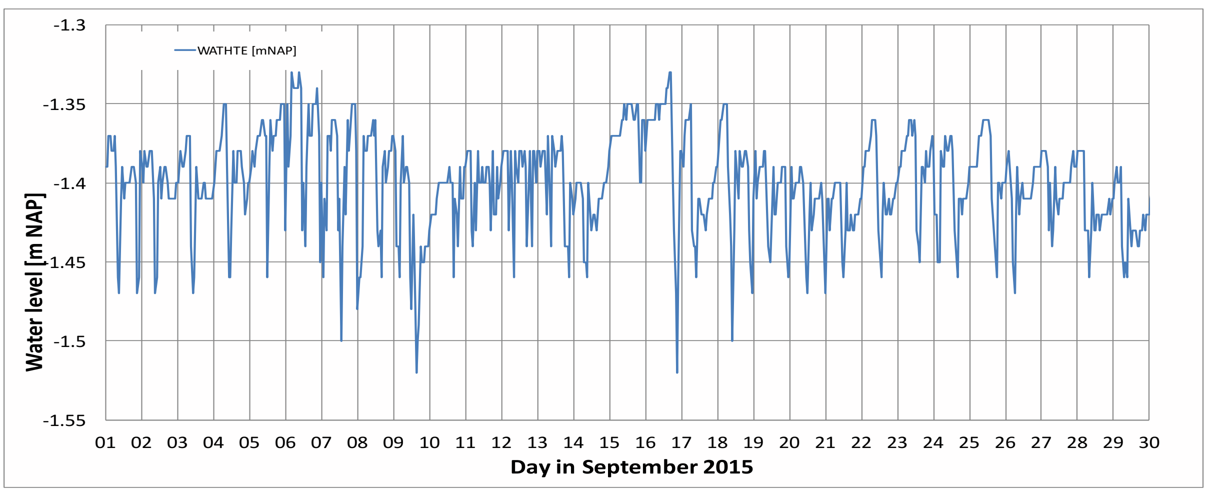

Figure 158: The water level at Termunterzijl.

The Woudbloem pump station has a capacity of 270 m^3 per minute. The pump drains an area of 5700 ha. The summer level is, according to the Watershap's web pages, -3.10 m NAP and the winter level is -3.50 m NAP. The recording in September 2015 (Figure 159) show levels of 1.0-1.15 m. The cause of the discrepancies are unclear at the moment.

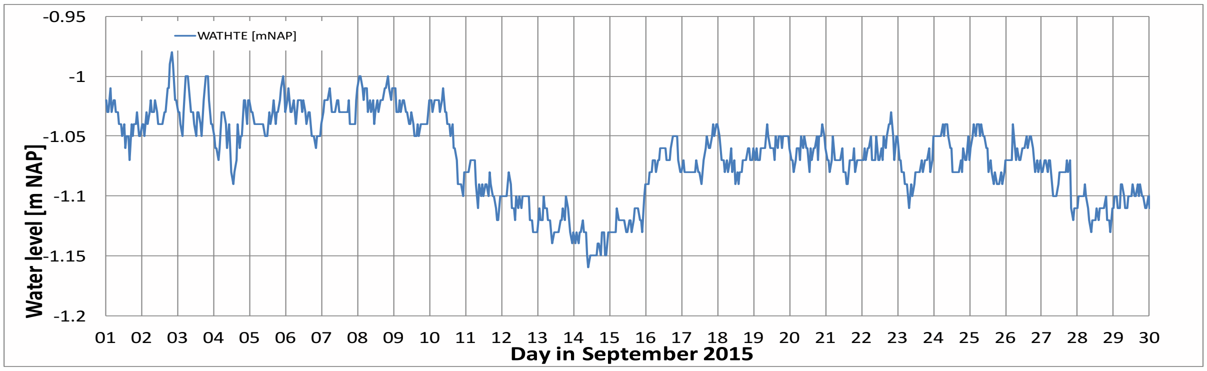

Figure 159: Water level at Woudbloem.

The Borgercompagnie pump has a maximum capacity of 112 m^3 per minute. The station drains an area of 285 ha. In this area, a summer level of -0.20 m NAP and a winter level of -0.60 m NAP is handled. In Figure 160, both the upstream and downstream levels are shown.

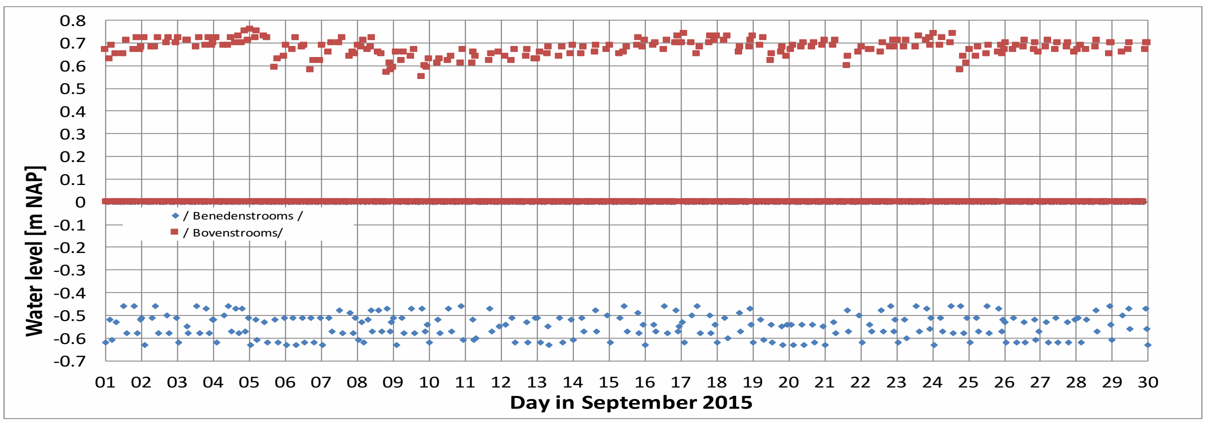

Figure 160: Water level upstream and downstream at Borgercompagnie.

Pump station Oostermoer, De Groeve (Drenthe), has a maximum capacity of 200 m^3 per minute. The station drains water from an area of 8000 ha. of Zuidlaardermeer. In this area is a summer level of -0.30 m of NAP and a winter level of -0.60 m NAP used. In September 2015 (Figure 161), the level was at about -0.60 m.

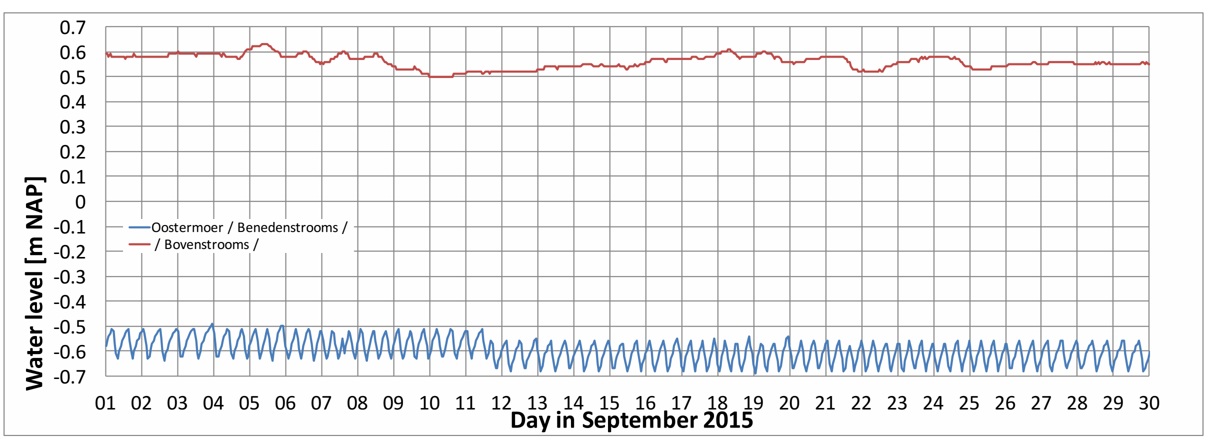

Figure 161: Water level upstream and downstream at Oostermoer.

Wildervank has a maximum capacity of 62 m^3 per minute. A 1.90 m height difference needs to be stepped up. An area of 875 ha south of Wildervank is drained. The winter level is set at +0.05 m relative to NAP and the summer level to +0.55 m relative to NAP. During September 2015 (Figure 162), the water level was gradually lowered towards the winter level.

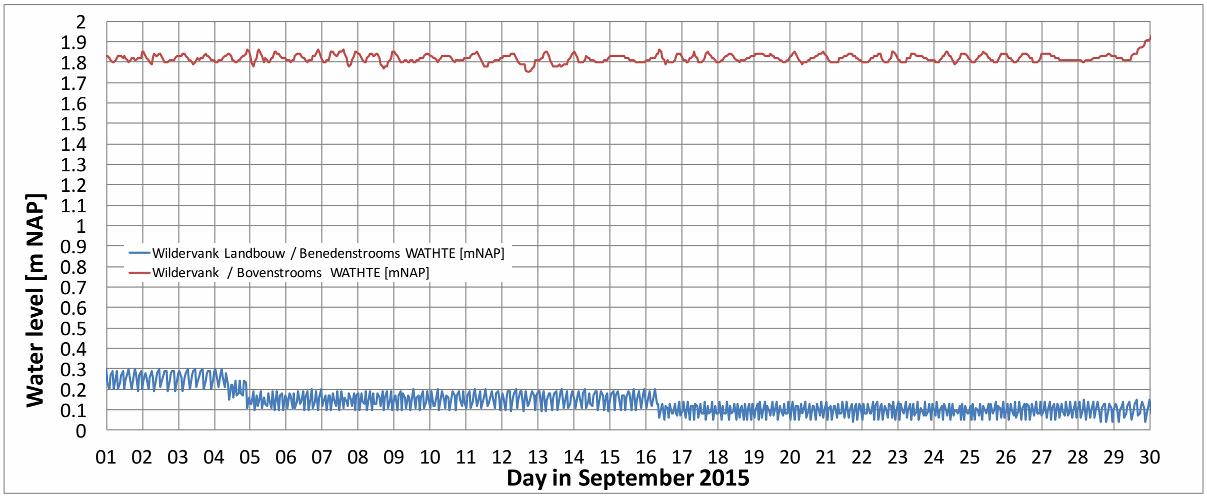

Figure 162: Water level at Wildervank, upstream and downstream.

Pump Wildervank Capital has one electric pump with a capacity of 23 m^3 per minute. The height difference is 1.50 meter. It drains the urban area of Wildervank and Veendam, a total area of 493 ha. The winter level in this area is set at 0.20 m NAP and the summer level at 0.30 m NAP.

15.3 Soil conditions

The top soil vary in the area from fine sand in the north, grading into silt, then clay, peat and finally sand again below the southernmost stations (Figure 163). Clay and sand may have very different ability to both contain and transport water.

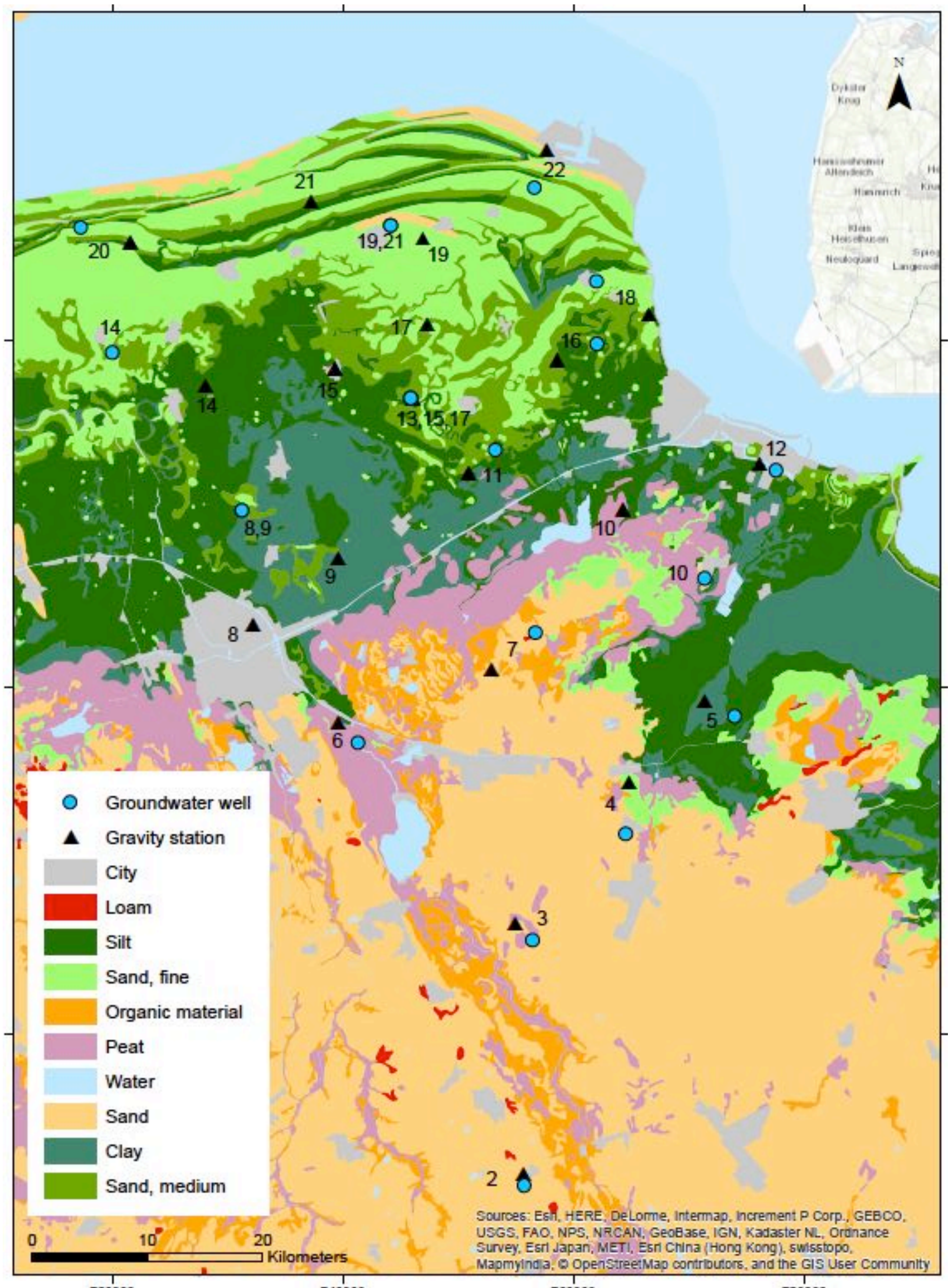

Figure 163: Dominating soil type for the uppermost 1.2 m. The locations of the gravity stations are indicated by black triangles. The lithological map was made by Alterra (2006) htp://www.wageningenur.nl/ and the stations were put on the map by Pitzer (2015). The map without gravity stations can be found on https://easy.dans.knaw.nl/ui/datasets/id/easy-dataset:37221.

15.4 Ground water measurements

Ground water is measured in monitoring wells. In the area of Waterschap Hunze en Aa's were three stations giving data in September 2015. These are shown in Figure 164. Station Zuiderveen does not have data after September 10th, and Froombosch have periods of missing data after September 16th. The ground water level rises on all stations after heavy rainfall, as can be seen in the correlation with the cumulative rainfall curve in Figure 164. After about 12 mm rain September 6th-7th, the ground water level increased about 10 cm at Oude Pekela and Froombosch, and about 40 cm at Zuiderveen. The peak occurred 1 ½ days later at Oude Pekela than at the two other stations. If lateral transport is ignored, this correspond to 12% yield for the two first sites and 3% yield for Zuiderveen.

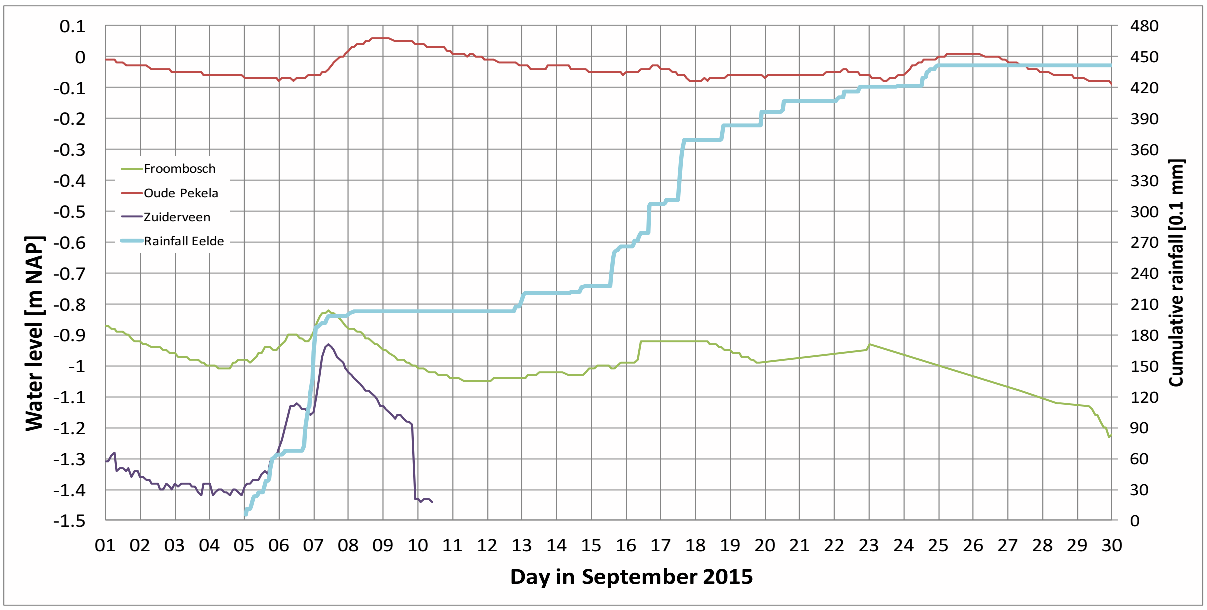

Figure 164: Ground water level recorded at three stations south of the Eems canal. Cumulative rainfall at Eelde is plotted with values at the right y-axis.

While the Froombosch and Zuiderveen stations are 10-20 m from a ditch, Oude Pekela is as much as about 500 m away. There may be drainage pipes in that agricultural field, but this is not known to us. A likely explanation of the delayed response and slower decay to the rainfall at Oude Pekala may be further distance from the dike. The difference in response is clearer observed in a longer time-series comprising the last four months of 2015 (Figure 165). Heavy rainfall in the second half on November, and particularly on November 16th, caused a rapid increase in ground water level; least rapid and of longest duration at Oude Pekela.

At station Froombosch, a 33 mm rainfall caused a groundwater rise of about 63 cm, implying a yield of about 5%. The soil in the area is described as sandy.

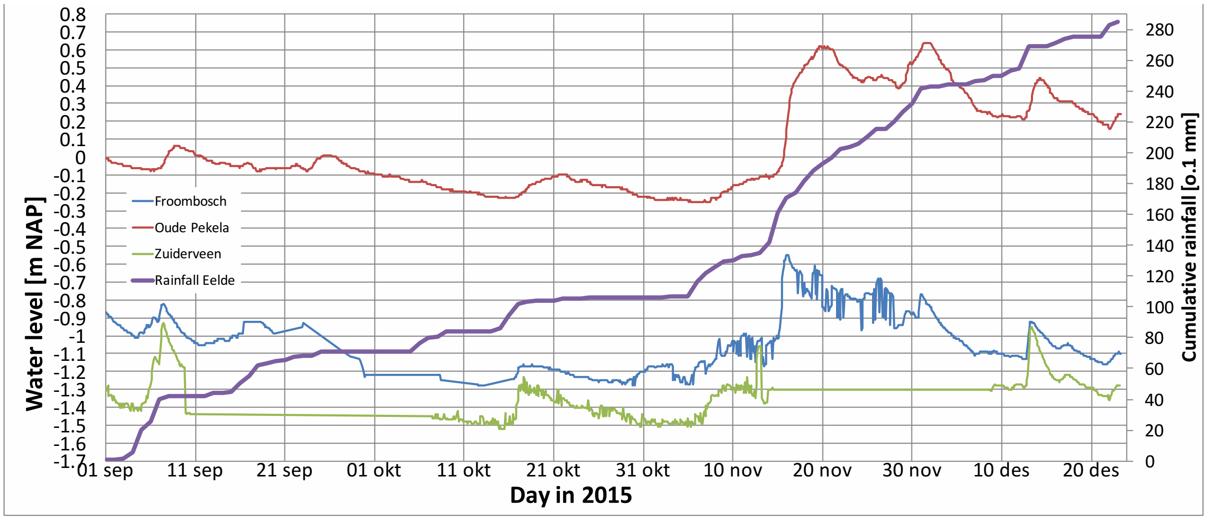

Figure 165: Ground water level recorded at three stations south of the Eems canal for the last four months of 2015. Cumulative rainfall at Eelde is plotted with values on the right y-axix

15.5 Estimates of ground water levels during previous surveys

Pitzer (2015) analyzed the DINOloket database of 17 groundwater wells, shown in Figure 166. Summer-winter fluctuations are clearly seen. The typical amplitude is difficult to see from the plot.

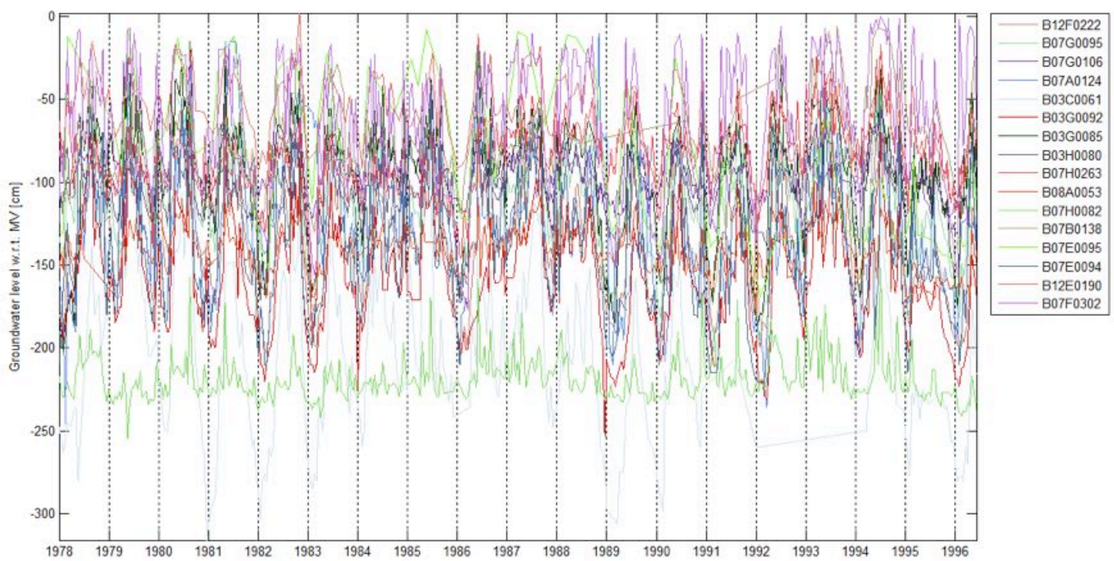

Figure 166: Ground water level from 1978 to 1996 for17 groundwater wells in the survey area (from Pitzer 2015).

Pitzer (2015) also investigated trends over the 1978-1996 time span (Figure 167), and found a decrease of 1-3.5 cm/year in the central parts of the field, and less, if any, significant change towards the rim. This pattern could possibly be related to the water management during subsidence; lowering the level where most subsidence occurs.

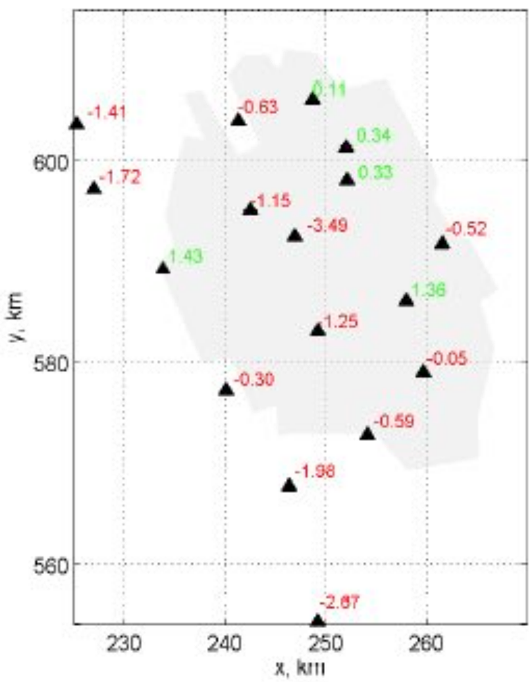

Figure 167: Trend of ground water change from 1978 to 1996. Red is a decrease and green an increase in level, in cm/year. From Pitzer (2015).

The ground water level near #2 Gasselte Church show fluctuations of up to 2 m over a 2-5 years period, with no obvious explanation.

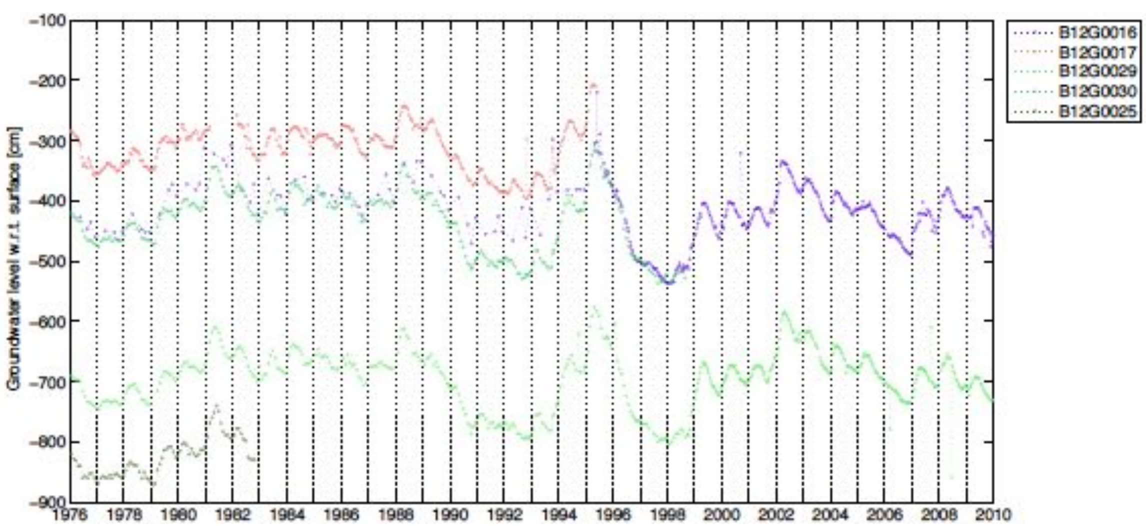

Figure 168: Ground water level from 5 different wells near station #2 Gasselte Church (from Pitzer 2015).

Pitzer (2015) discusses the value of specific yield, S_y, to use in a gravity groundwater correction, and refers to average values of 0.18 for silt and 0.26 for medium sand. These are much higher than the values found in the comparison of rainfall and ground water level (page 134).

We have not attempted at applying ground water corrections in this processing. The topic needs to be better understood for the Groningen area. When that is achieved, future monitoring will probably benefit from hydrology corrections.

16 Salt mining

Salt mining occur at three locations within the survey area; Veendam, Winschoten and Zuidwending (Figure 169).

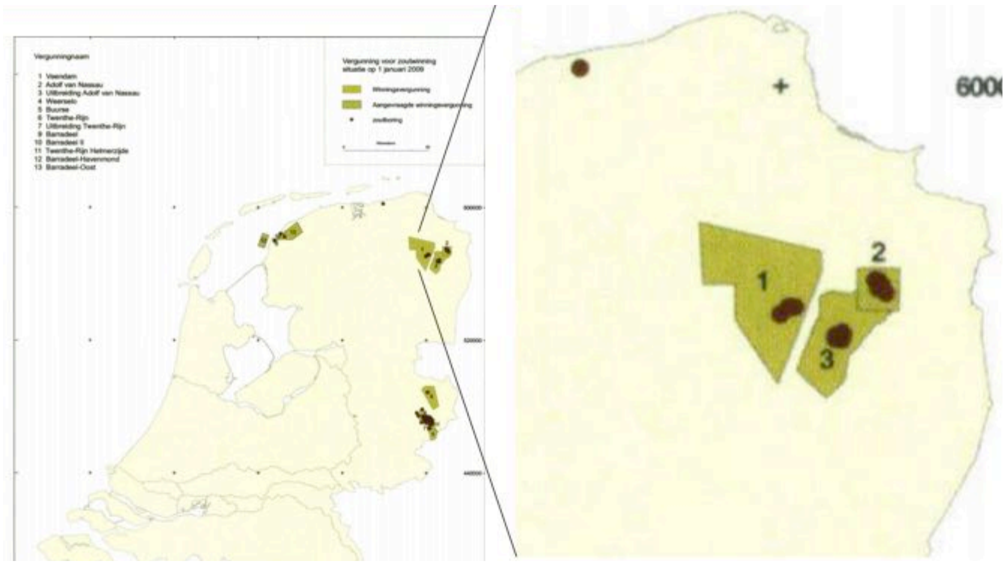

Figure 169: Salt mines in the area. 1: Veendam, 2: Adolf van Nassau, 3: Extension Adolf van Nassau

The activity west of Veendam has been ongoing since 1993, and cause up to 1.5 cm/year subsidence in an area of 3-4 km radius (Figure 170). Maximum subsidence was 32 cm by early 2014. From 2005 to 2015, about 250 ktons were net extracted, from depths of 1300-1700 m. The gravity anomaly may be of similar shape as the subsidence bowl. Active water management is done to prevent a general rise of the water level in the ditches in this area. The nearest station, #158 Veendam church, is 3 km away and is barely influenced by the subsidence; less than 1/10 of the maximum according to Figure 170. Station #3 Annerveen is 4 km away from the center and is probably not influenced significantly either.

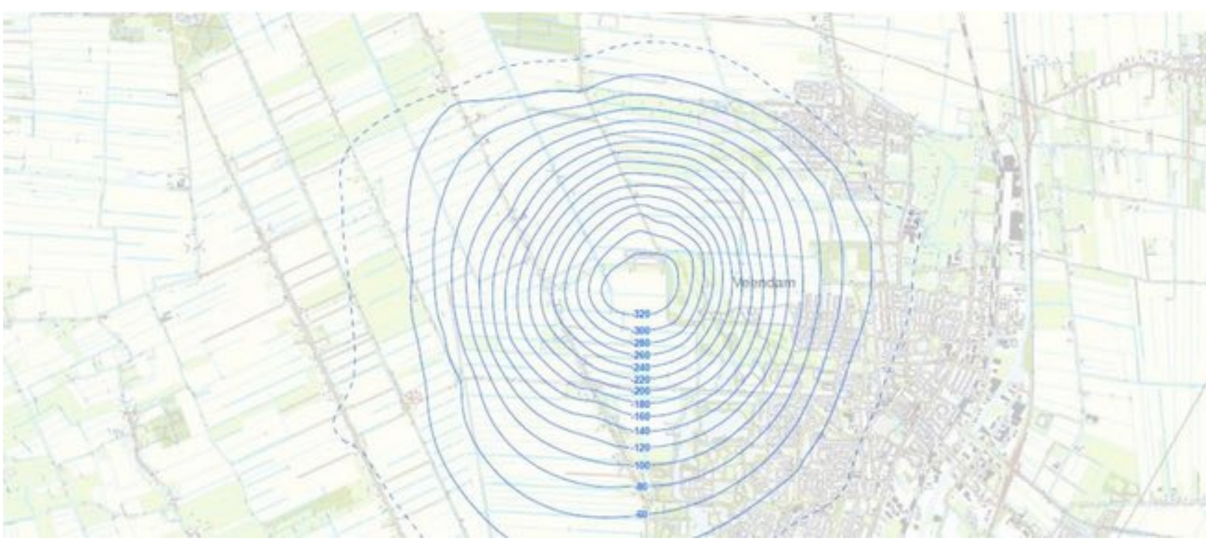

Figure 170: Subsidence caused by salt extraction west of Veendam, in mm. From http://www.nedmag.nl/omgeving/bodemdaling.

A point mass approximation was used to determine gravity change at the surface caused by salt mining, at a depth of 1500 m. This was done by Marcin Glegola, Shell, and shown in Figure 171. Maximum signal at Veendam was -6.4 μGal (for 2015-2005), and only -0.24 μGal at the closest time-lapse gravity station. No production data is available prior to 2005. An upper bound may be the same production rate before as after. That gives a peak signal in the 2015-1978 time span of -24.3 μGal and -0.9 μGal at the time-lapse gravity stations #3 and #4 (Figure 171).

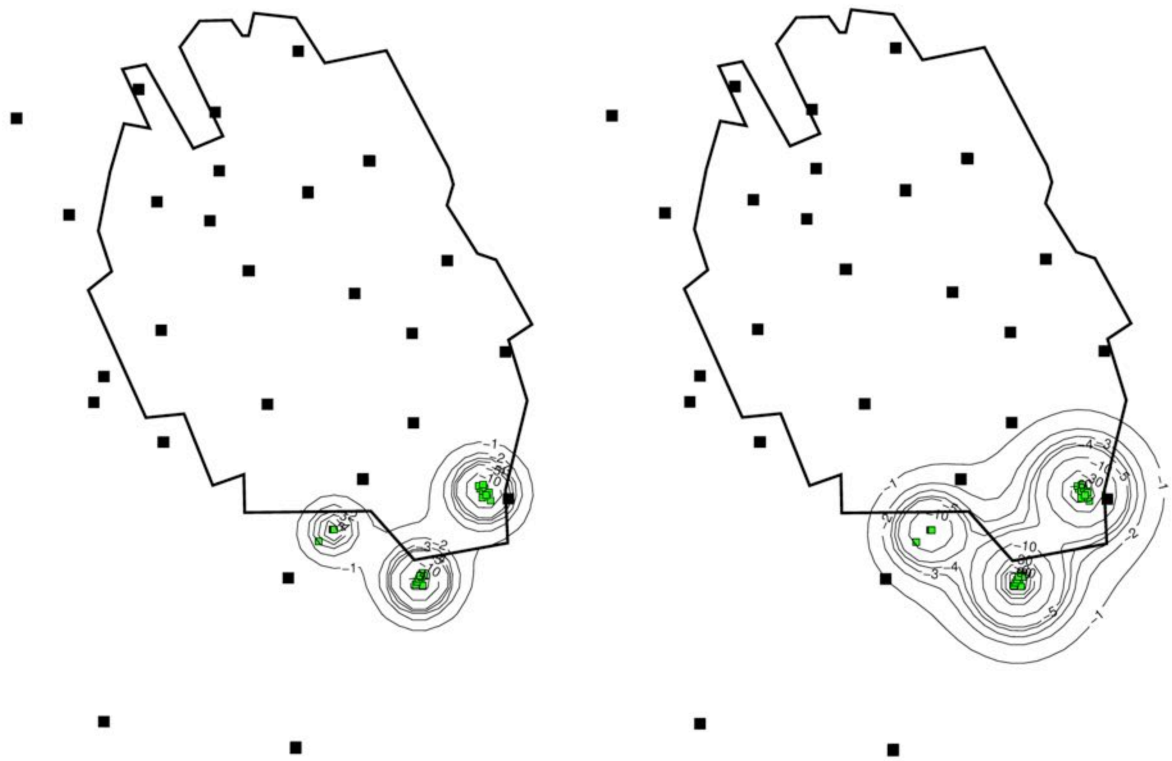

Figure 171: Modeled gravity response from all three salt mines, 2015-2005 (left) and 2015-1978 (right).

Production at Winschoten started in 1954, and at Zuidwending in 1967. A 1200 m depth to the point mass is assumed. Gravity station #32 Winschoten was measured in 1984 and 1988, and a gravity change of -4.9 μGal is estimated in this period.

At Zuidwending, a depth of 900 m was used for the point mass estimate. This cause a maximum change at a time-lapse gravity station of -0.4 μGal for the period 2015-1978.

17 Time-lapse gravity

17.1 Time-lapse relative scale factor calibrations

The scale factors of Bilker (1996) were first applied to the 20th century surveys, and the scale factors from the Monschau calibration survey to the 2015 survey. Then plots of time-lapse gravity change vs. gravity values were made for all time-lapse combinations, to optimize scale factors further. The calibration survey from #2 Gasselte via #29 Zwolle to #23 Maastricht has been processed as a separate mini-survey, named 2015B, to compare with the 1984 and 1988 surveys. The gravity ranges of coincident stations in various survey pairs are shown in Table 49. Only the 2015-1984 and 1988-1984 surveys exceed the 39 mGal between stations #2 Gasselte and #22 Uithuizermeeden. The slope of best-fit lines through all reference stations (defined in Chapter 17.4), after correcting for subsidence and model changes have been calculated. Examples of such cross-plots with fitting lines are shown in Figure 172 for the Zwolle and Maastricht calibrations. There is clearly some need for adjustment of scale factors. After a global optimization of the scale factors in all surveys except 2015, which was kept fixed, the slopes of all fitting line residuals are shown in Table 50. The Gasselte to Maastricht calibration was given 4 times the weight of the others, and the Gasselte to Zwolle twice the other calibrations, due to their larger gravity range. Slope residuals are up to 3.9 x 10^{-4}, which may be seen as an indication of the uncertainty in scale factors.

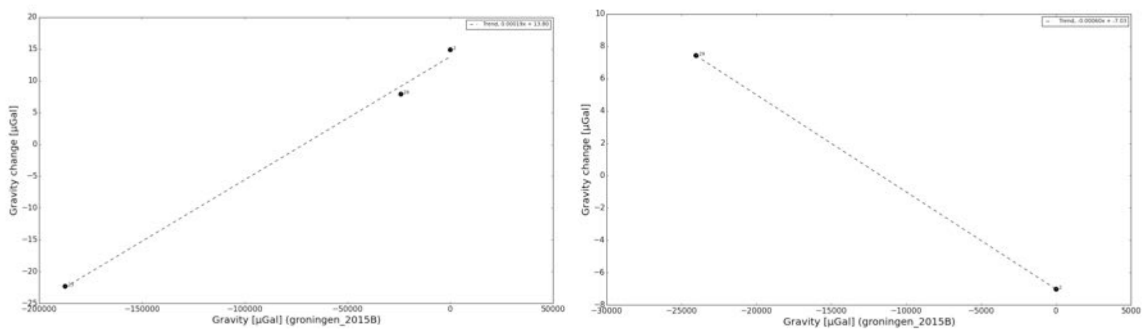

Figure 172: Gravity change vs. gravity. Left: For 2015-1984 for stations 2, 23 and 29. Right: 2015-1988 for stations 2 and 23.

	1978	1984	1988	1996	2015	2015B
1978		39	39	39	39	
1984			63	39	39	187
1988				39	39	24
1996					39	

Table 49: Maximum gravity range for reference stations of various survey pairs, in [mGal].

	1978	1984	1988	1996	2015	2015B
1978		-1.9	1.7	-0.5	0.9	
1984			-0.9	1.6	3.3	-1.8
1988				-2.5	-3.9	6.0
1996					-1.2	

Table 50: Residual slope fit after global optimization of scale factors, in 10^{-4}.

The adjustment terms added to the scale factors of the previous surveys are shown in Table 51. Cross-plots involving the 2015-survey, after scale factors have been adjusted, are shown in Figure 173.

1978	1984	1988	1996
-0.8	0.2	5.7	3.8

Table 51: Final scale factor adjustments, in 10^{-4}.

The uncertainty in the scale factors are still significant, estimated from the scatter in Table 50 to have a standard deviation of about 2.5×10^{-4}.

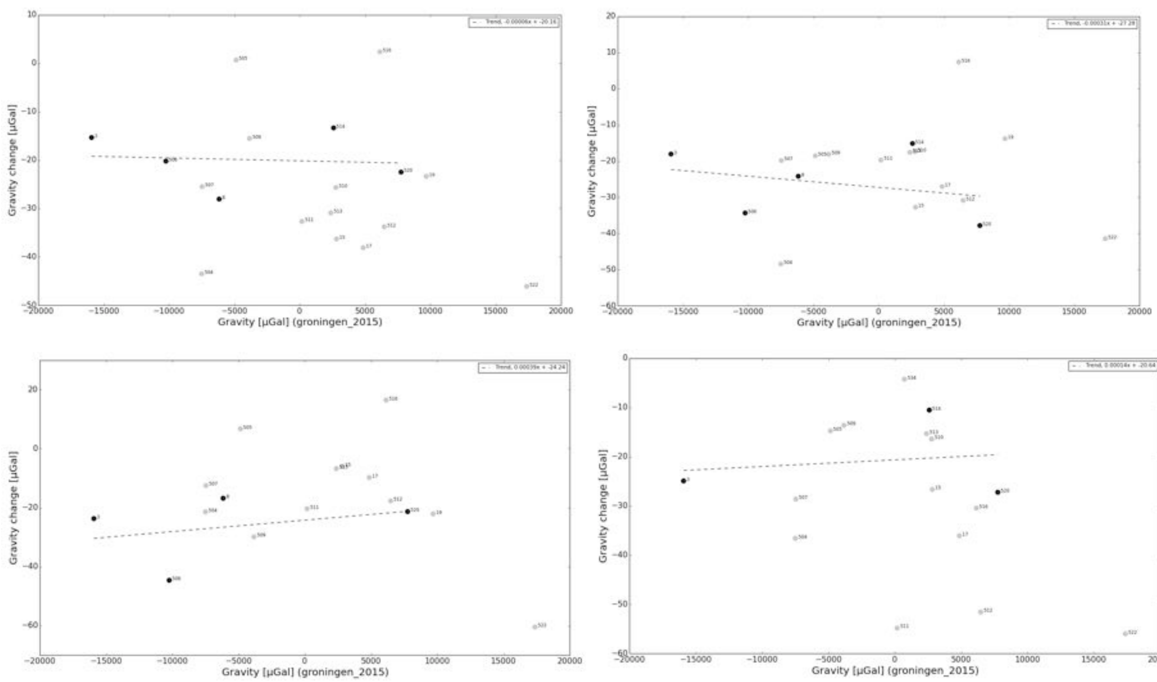

Figure 173: Gravity change vs. gravity. Upper left: 2015-1978, upper right 2015-1984, lower left 2015-1988, lower right 2015-1996. Reference stations are marked in black, other stations in grey. Data have been subsidence corrected, and modeled gravity changes have been subtracted from the data.

17.2 Subsidence

Subsidence data for the pre-2015 surveys are given in Bilker (1996) and shown in Table 52. Initial heights are from Strang van Hees (1980). Details on how the measurements were done, and the associated uncertainties, was not available. Subsidence data 1996-2015 are from a model provided by NAM. Examples of the data in map view are shown in Figure 174. Some anomalous values compared to neighbors in time and space are #6 and #14 in 1984 and #7 in 1988, all deviating 1-3 cm from "smooth" values. This may indicate an uncertainty (standard deviation) of 1-3 cm in the data. The peak subsidence is offset to the north-west from the center of the field, with station #13 having a maximum of 26.5 cm from 1978 to 2015. The rate of subsidence was up to about 1.3 cm/year between 1978 and 1984, slowed down between 1984 and 1996 and increased again up to a maximum of 7 mm/year between 1996 and 2015. Time-development an selected stations are shown in Figure 175. Subsidence 1978-2015 at the 7 to 10 stations that potentially can be used to determine the zero-level for gravity changes (see Chapter 17.4) range from 3 mm (station #2 Gasselte) and up to 10.2 cm (station #8 Sint Fransiscuskirk), with an average of 5.5 cm. These stations are in the supplied data and models relatively more affected by subsidence than by modeled gravity, for some reasons. There are no gas field immediately west of the Groningen field that could contribute to such subsidence (Figure 176). Pressure depletion in the aquifer west of the field (Southern Lauwerszee Through Aquifer, see Figure 177) can potentially cause subsidence at stations #6, #8 and #30, while stations #14 and #20 are above an aquifer believed not to be connected to the gas reservoir. Station #3 Annerveen is situated above a separate gas-producing structure, and subsides probably due to that.

No	Station name	Height 1978 (NAP)	1984-1978	1988-1978	1996-1978	2015-1996
2	Gasselte church	17.84	0	0.001	0	-0.003
3	Annerveen	2.05	-0.02	-0.034	-0.05	-0.030
4	Tussenklappen	-0.43	-0.01	-0.036	-0.05	-0.077
5	Roode Til	-0.63	-0.03	-0.034	-0.04	-0.068
6	Haren	0.50	0.01	-0.017	-0.03	-0.051
7	Kooipolder	-0.28	-0.03	-0.054	-0.05	-0.085
8	Goningen Sint Fraciscuskerk	0.92	-0.02	-0.030	-0.04	-0.062
9	Ten Boer	-0.34	-0.04	-0.060	-0.08	-0.077
10	Schildmeer	-0.85	-0.05	-0.044	-0.07	-0.093
11	Ten Post	-0.15	-0.04	-0.067	-0.10	-0.135
12	Delfzijl	0.06	-0.03	-0.059	-0.08	-0.069
13	Stedum	1.18	-0.08	-0.109	-0.15	-0.115
14	Winsum	0.86	-0.02	0.001	0.01	-0.043
15	Middlestum church	3.07	-0.04	-0.068	-0.10	-0.076
16	Leermens	1.13	-0.06	-0.078	-0.10	-0.117
17	Garsthuizen Garage	2.20	-0.08	-0.113	-0.14	-0.101
18	Bierum	1.21	-0.03	-0.056	-0.07	-0.099
19	Uithuizermeeden church	2.81	-0.07	-0.073	-0.10	-0.079
20	Eenrum	1.64	0	-0.021	-0.03	-0.025
21	Usquert	1.73	-0.02	-0.035	-0.05	-0.045
22	Uithuizermeeden	1.85	-0.04	-0.058	-0.09	-0.080
30	Groningen NS	3.421	1984 = reference	-0.010	-0.02	-0.039
33	Assen NS	11.146	-	-	1996 = reference	-0.004
34	Wagenborgen OM	1.264	-	-	1996 = reference	-0.082
35	Gasselte OM	15.009	-	-	1996 = reference	-0.003

Table 52: Height and subsidence for the pre-2015 stations, in meters.

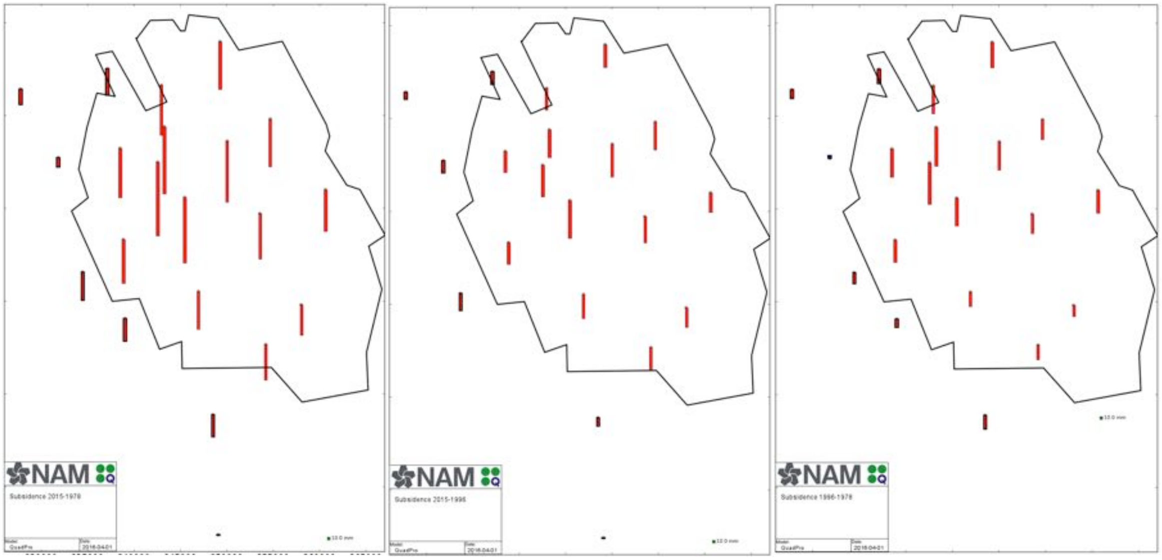

Figure 174: Subsidence data for: 2015-1978 (left), 2015-1996 (middle) and 1996-1978 (right).

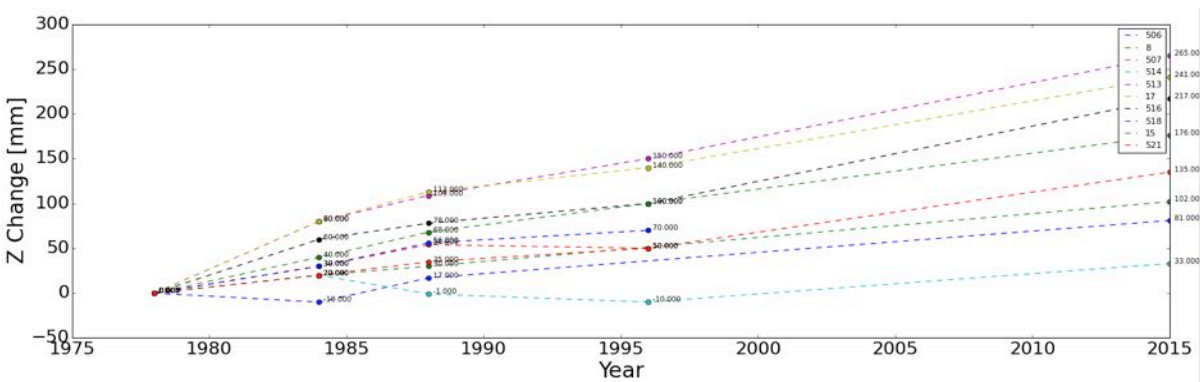

Figure 175: Subsidence development through time compared to 1978 at some stations.

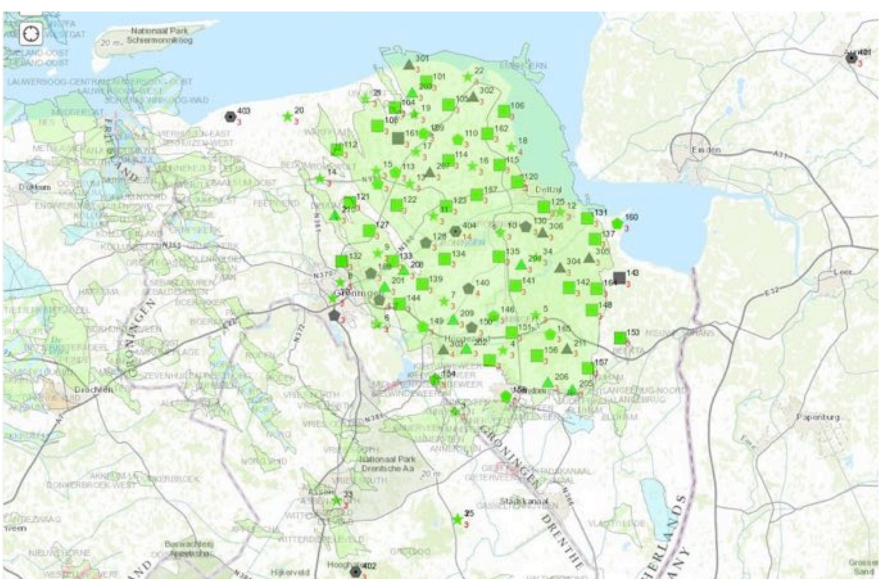

Figure 176: Map of stations and underlying gas reservoirs (provided by NAM).

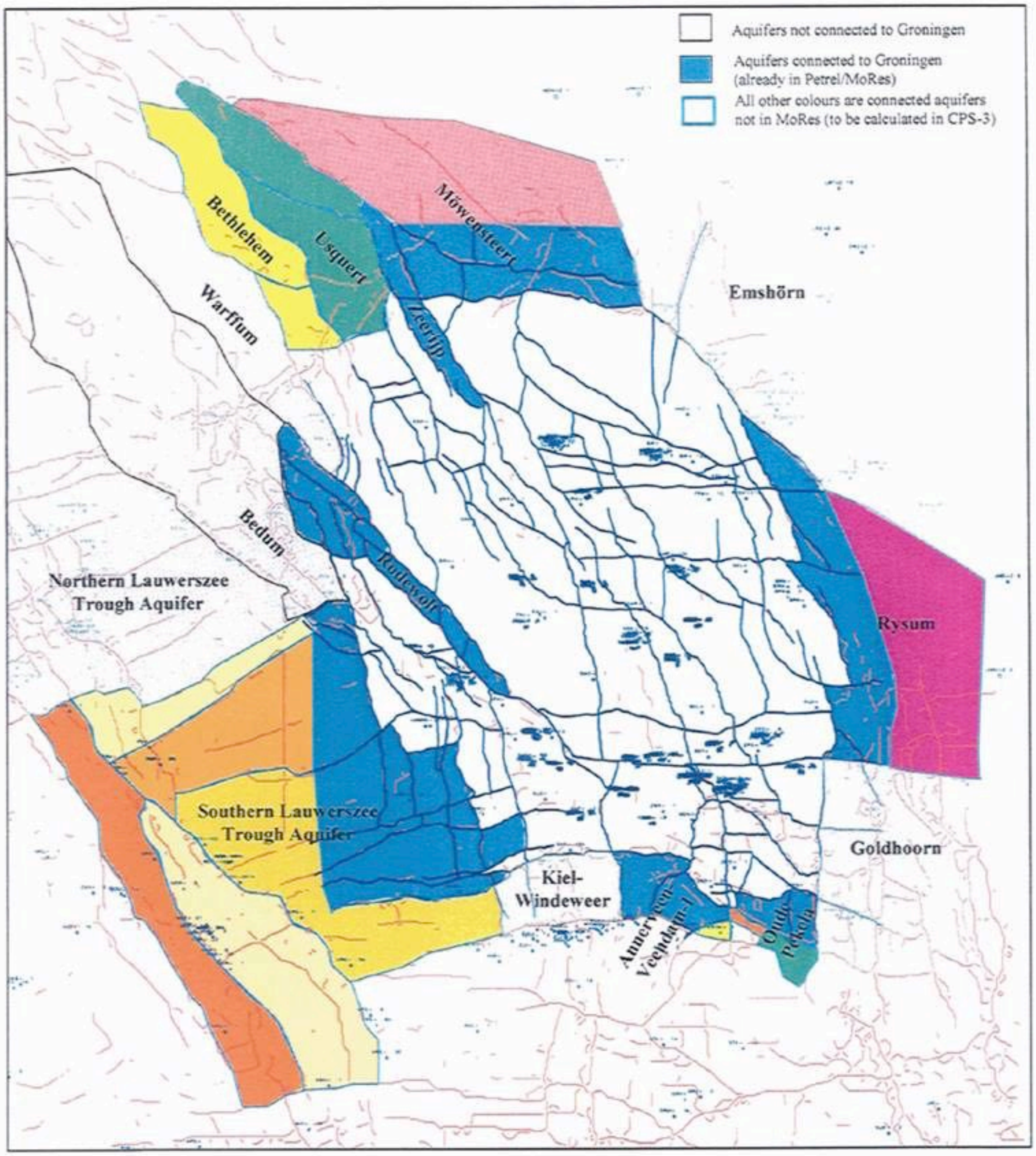

Figure 177: Overview map of aquifers. From Shell.

We have assigned a height uncertainty (standard deviation) of 1.5 cm to the pre-2015 surveys, but realize there is little data available to assess errors. This uncertainty transforms to a subsidence uncertainty of 2.1 cm and a time-lapse gravity uncertainty of 6.5 μGal.

Marcin Glegola of Shell has done additional subsidence modeling based on a dynamic reservoir model and a semi-analytic Geertsma model. The modeling gives significantly less subsidence than the values presented above for stations #13 and #17; 2.5 cm less for 1984-1978 increasing to 4 cm for 1996-1978. This Geertsma model also gives less subsidence at the reference stations than the data; on average about 8 mm for 1984-1978 and 1988-1978 increasing to 18 mm for 1996-1978 and 2015-

1978. Standard deviation between model and data is 14 mm for 1984-1978 and 1988-1978 increasing to 21 mm for 1996-1978 and 29 mm for 2015-1978. It is difficult to judge how much of these deviations are due to data errors and how much due is to modeling errors. This could be worth looking further into.

For station #30 Groningen we have assumed the subsidence is similar to 8 Sint Fransiscuskirk. For 32 Windschoten NS and 33 Assen NS we ignored subsidence. For 34 Wagenborgen we have taken the average subsidence of the three neighboring stations 5, 10 and 12. For 35 Gasselte OM we have used the same subsidence as 2 Gasselte church.

17.3 Modelled gravity changes and subsidence

Modelled time-lapse gravity changes (caused by reservoir mass changes only, ignoring subsidence) have been received from NAM, and can be used for adjusting the zero level, for Quality Control and for comparisons after the final processing. The gravity reduction 2015-1996 is modeled to be up to 27 µGal and 2015-1978 up to 59 µGal (Figure 178). The modeled rate of change at maximum (station #10) has over these years decreased from -2.2 µGal/year to -1.4 µGal/year. Stations #2, #14 and #20 all have modeled gravity reductions 2015-1978 less than 1.8 µGal, and can therefore with reasonable confidence be used as reference stations. Stations #3, #6, #8 and #21 have modeled gravity reductions of 4.7 µGal or less, which is 7% or less of the maximum signal. All these stations can help determining the zero level. Stations #30, #33 and #35 are outside the field and can also be used for determining the zero level. The average gravity changes 2015-1978 for these 10 stations is -2.4 µGal.

In a depleting reservoir with homogeneous rock compressibility, one would expect gravity change and subsidence to be related through one scalar. Two clear deviations are the subsidence peak offset to the northwest of the modeled gravity peak, and the larger subsidence at the western rim of the field. A reason for the latter could be that the pressure drop has propagated significantly into the water zone west of the reservoir. Such an effect has not been included in the gravity change model. An average subsidence of 5.5 cm and equivalent compaction of the reservoir will also mean removal of 5.5 cm of water causing a 2.3 µGal gravity reduction. Water expansion due to pressure drop will cause further gravity reduction, dependent on the vertical column of change. This number is small, but not insignificant, compared to the direct subsidence effect on gravity (17.0 µGal).

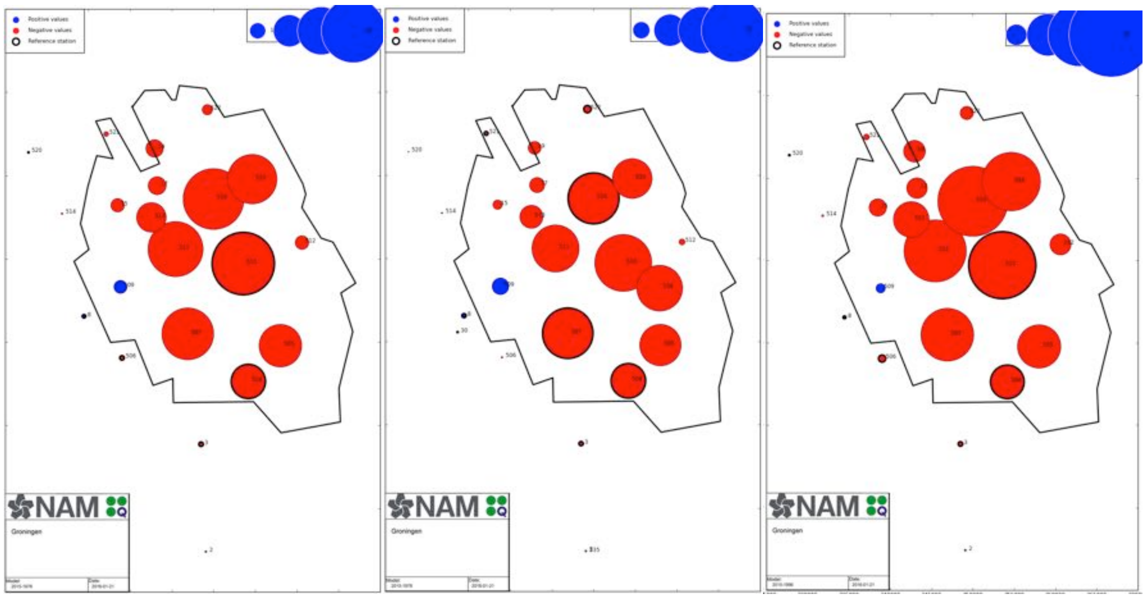

Figure 178: Modeled gravity changes (not including subsidence) for: 2015-1978 (left), 2015-1996 (middle) and 1996-1978 (right). Values are proportional to the radius of the circles.

17.4 Reference stations

Ten stations; #2, 3, 6, 8, 14, 20, 21, 30, 33, 35, have modeled gravity reductions <4.7 µGal for 2015-1978, and are potential reference stations. There are important for assessing the quality of time-lapse data and for determining the zero-level in each survey, and we started with examining these data closely. We first checked the processed measurements for outliers, and found:

- Station #30 Groningen NS has in 2015 about 54-66 µGal higher value than in the three earlier visits. The measurement is clearly an oddity and is taken out. A possible explanation of this which has not been checked out is whether a space beneath the site (a basement) has been filled with mass between 1996 and 2015.
- Station #33 Assen NS has a gravity increase of 48 µGal from 1996 to 2015. We have no explanation for this, but have taken out the measurement (this station was only measured in 1996 and 2015).
- Stations #6 Haren and #8 Sint Frasiscuskirk are outliers in 1996; about 30 µGal higher and lower respectively of those both before and after. They have been omitted from further analysis.
- Station #14 Winsum in 1988 is about 15-20 µGal lower than both before and after (Figure 179) and would be the next measurement considered an outlier. However, it resembles the signal on neighboring stations #15, #13 and #17 inside the field, and has been kept in the further analysis. A consequence of omitting this station would be to move the reference level in 1988 up 3.8 µGal, causing a larger discrepancy between observed and modeled values.

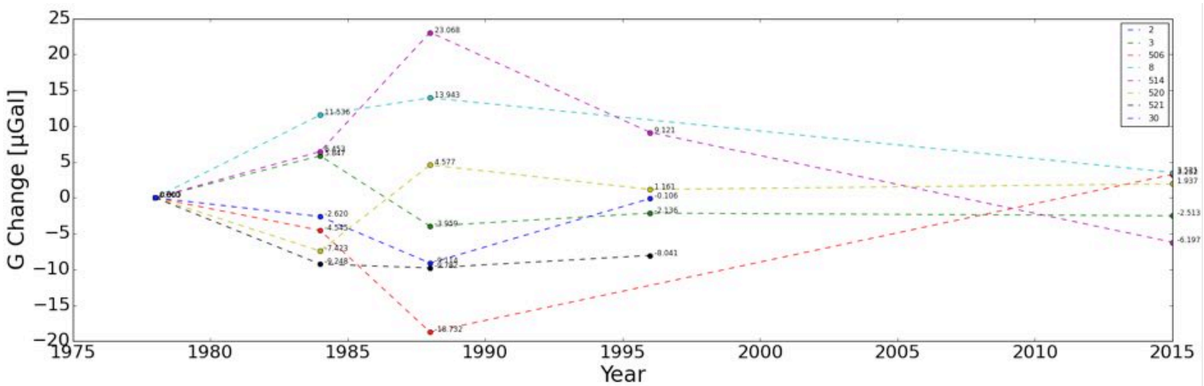

Figure 179: Observation minus model deviations from mean of reference sites for all reference sites in the Groningen surveys. Stations 33 and 35 have been omitted from the plot.

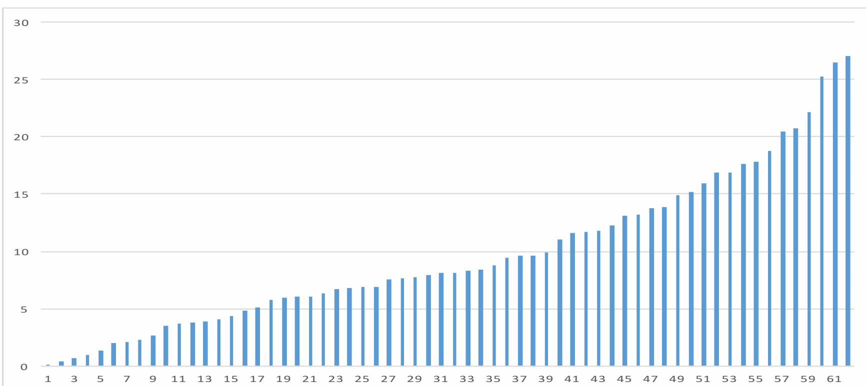

Figure 180: Time-lapse residuals of all time-lapse pairs of reference stations after editing, sorted in ascending order. Values in µGal.

The distribution of all time-lapse difference residuals (measurement minus model) for the reference stations, after this editing, is shown in Figure 180. Standard deviation is about 10 µGal. The three largest residuals are related to station #2 Gasselte and #21 Usquert in 2015, and these two measurements also cause several other high residuals, and the measurements were for that reason omitted in the further processing. Further, the value at #35 Gasselte was in 2015 adjusted to agree with #2, as described on page 99. It has no independent information and was removed as well. The resulting table of residuals is shown in Table 53. Now 8 measurements out of 41 (20%) were omitted.

Difference/ station	84-78	88-78	96-78	15-78	88-84	96-84	15-84	96-88	15-88	15-96	Std.
2 Gasselte	4.8	5.6	9.1		1.0	5.1		2.7			2.5
3 Annerveen	-3.9	1.1	8.7	10.6	5.2	13.5	12.5	6.9	7.3	-2.6	5.7
6 Haren	6.8	16.8		3.8	10.2		-5.0		-15.1		10.4
8 Groningen Sint Fra..	-11.6	-19.1		-6.5	-7.3		3.2		10.5		9.7
14 Winsum	-6.9		-12.2	2.7		-4.4	7.7			10.5	8.1
20 Eenrum	6.0	-9.9	-7.0	-10.5	-15.7	-12.2	-18.5	2.1	-2.7	-7.9	7.2
21 Usqert	8.1	5.5	1.4		-2.5	-5.9		-4.8			5.2
30 Groningen NS					9.2	3.8		-6.8			6.6
33 Assen NS											
35 Gasselte OM											
Number of observation	7	6	5	5	7	6	5	5	4	3	
Standard deviation	7.3	11.6	8.5	7.6	8.6	8.4	10.9	5.1	10.0	7.7	
Zero-level uncertainty	2.7	4.7	3.8	3.4	3.3	3.4	4.9	2.3	5.0	4.5	

Table 53: Time-lapse gravity changes in μGal; measurement minus model, for all stations defined as reference. Omitted values are marked in red.

After this editing, the standard deviation of time-lapse changes of reference stations within a survey difference can be plotted against the time span (Figure 181). There is no significant increase in the scatter with time.

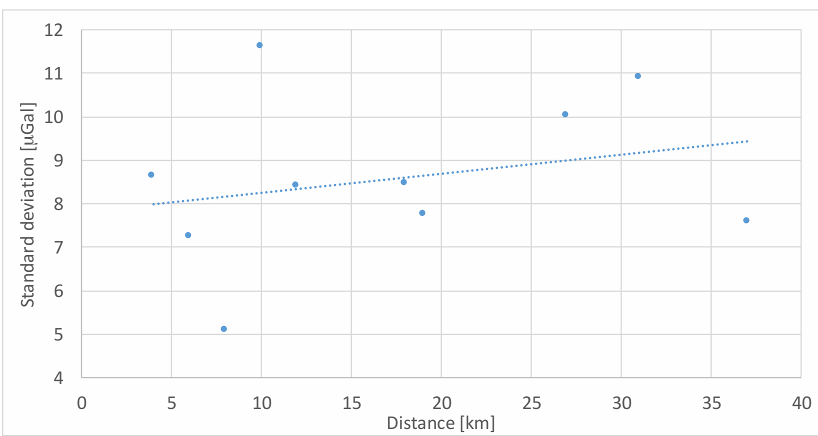

Figure 181: Standard deviation of reference stations (observations minus model) for all pair of surveys vs. time between surveys, after editing out 8 measurements.

The standard deviations of all stations in a survey-pair may be tabulated according to the surveys involved, as shown in Table 54. From these data, we may predict time-lapse uncertainties of about 9 μGal (standard deviation). The differences involving the 1996-survey have on average lower values than the others, suggesting the time-lapse quality is better for this vintage.

	78	84	88	96	15	Average
78		7.2	11.6	8.5	7.6	8.7
84	7.2		8.6	8.4	10.9	8.8
88	11.6	8.6		5.1	10.0	8.8
96	8.5	8.4	5.1		7.7	7.4
15	7.6	10.9	10.0	7.7		9.1

Table 54: Standard deviation of all reference stations (measured - modelled) per survey pair, and average values for all with a particular year involved.

17.5 Reference (zero) level between surveys

The zero-level for each survey can be set as the average of the reference stations, after correcting for the subsidence effect on gravity and the modeled change in gravity attraction from the reservoir changes. As shown in the bottom row of Table 53, formal uncertainties in the average estimate range from 2.3 to 5 μGal. The resulting time-lapse maps; without subsidence correction, but with the zero-level determined after subsidence corrected, are shown in Figure 182. The maps show a consistent gravity decrease over the field in 1984-1978 and 1988-1978, with more variable direction of changes in 1996-1978 and 2015-1978.

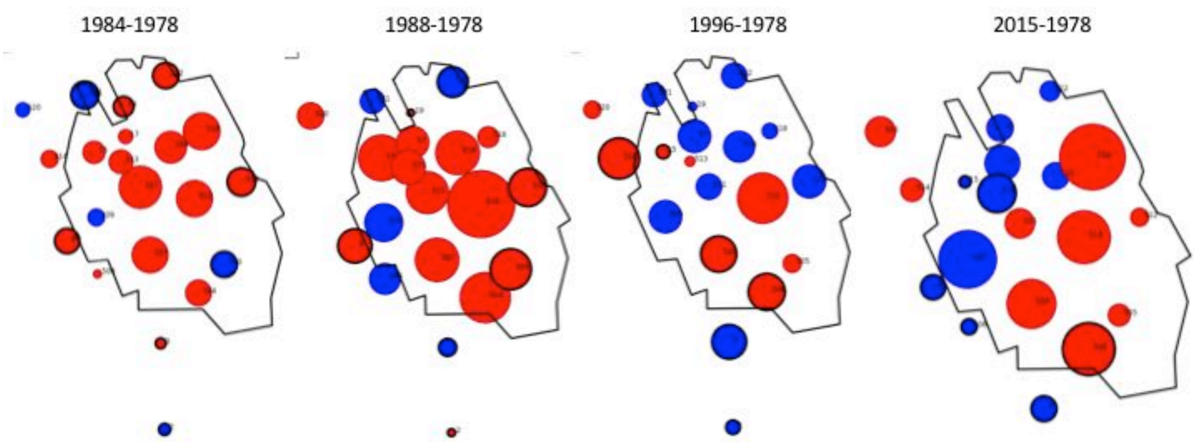

Figure 182: Time-lapse maps without subsidence corrections for changes with respect to 1978. Red means gravity decrease and blue gravity increase. Values are proportional to area of circle. The zero-levels of the plots are adjusted such that the average of the reference stations is zero after adjusting for subsidence and modeled gravity change.

Gravity changes with respect to 1978 after subsidence correction are shown in Figure 183. Over central parts of the field, a strong and consistent decrease in the time-spans 1984-1978 and 1988-1978 changes to an increase 1996-1988. This is surprising in view of the steady gas production in the whole period (Figure 184), which should cause a steady gravity decrease. A steady decrease is also what the modeling predicts.

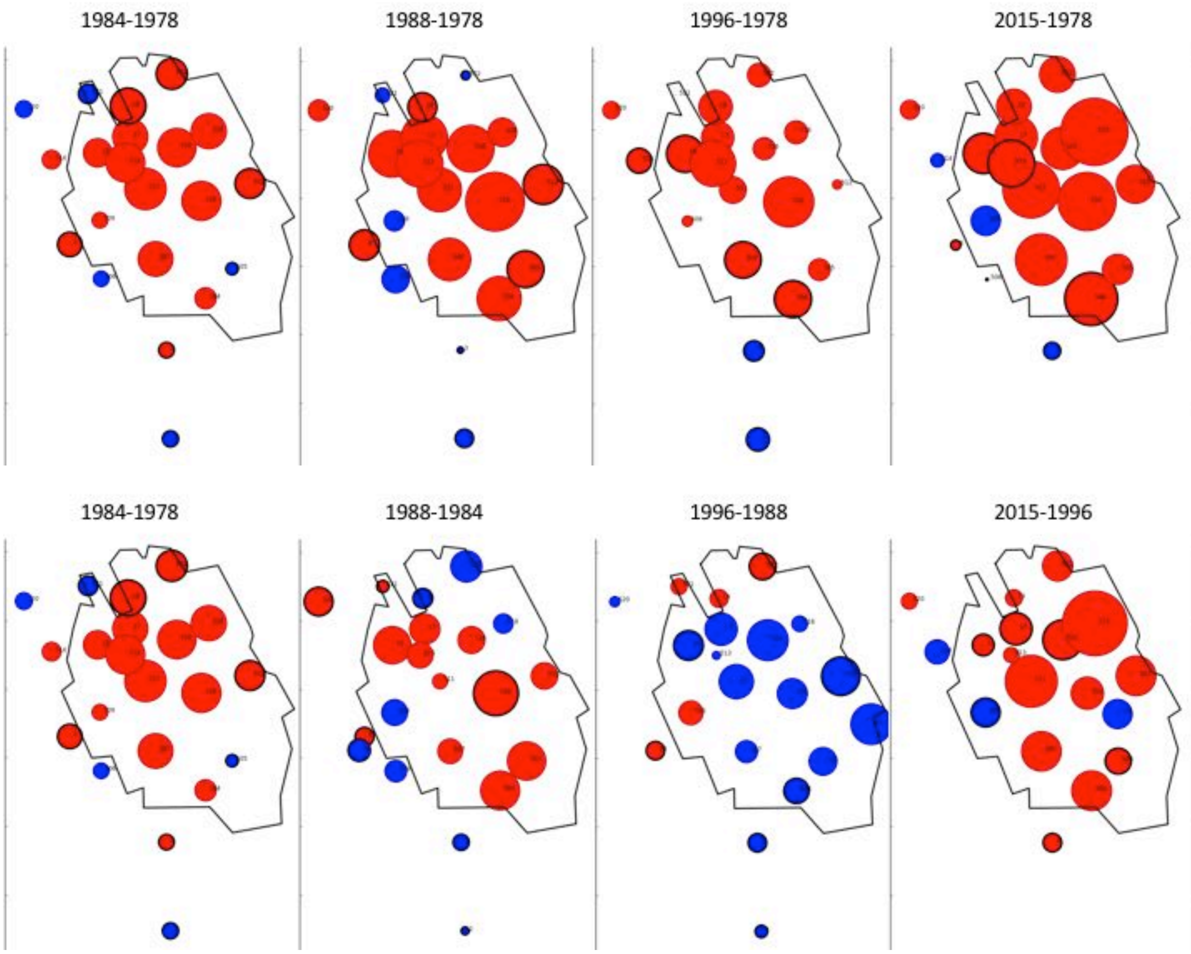

Figure 183: Time-lapse maps after subsidence correction, for changes with respect to 1978 (above) and for running time intervals (below). Red means gravity decrease and blue gravity increase. Values are proportional to area of circle. The zero-level of the plots are adjusted such that average of reference stations after subsidence and model corrections are zero.

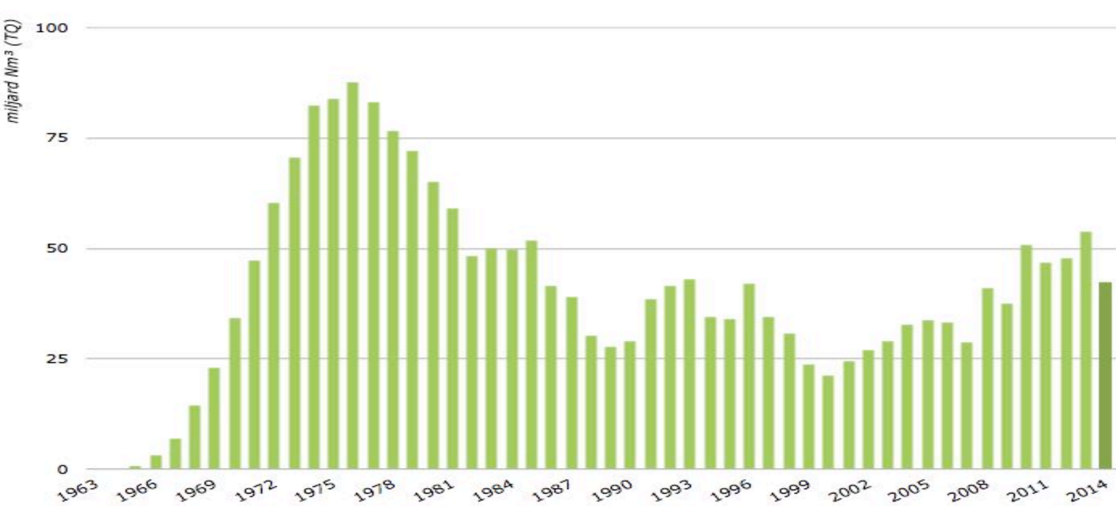

Figure 184: Gas production per year from the Groningen field (source: NAM).

Residuals of observed-modeled gravity changes (Figure 185) are significant and show coherent spatial patterns. Particularly the 1984-1978 and 1988-1978 changes are up to 15-30 µGal larger than the model in central and northern parts of the field. We have investigated whether the discrepancy can be caused by zero-level errors or some other artifacts.

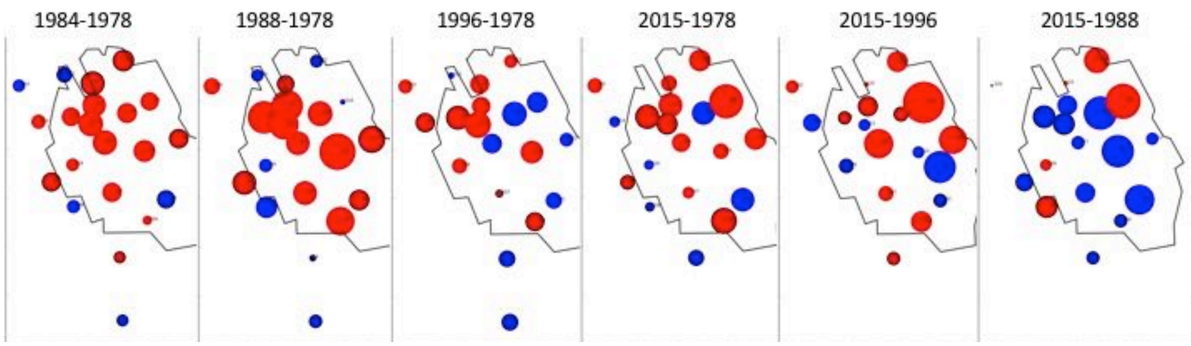

Figure 185: Difference maps of observed-modeled gravity changes, for 6 selected time-lapse intervals. Red means gravity decrease and blue gravity increase. Values are proportional to area of circle.

If the gravity model on average is correct, the zero-level can be defined by best match of *all* stations, inside and outside the field, not only the reference stations. Comparisons of the different zero-level calculations are shown in Figure 186. The model fit changed the zero levels compared to using reference stations as listed in Table 55. Time-lapse intervals involving the 1988 survey caused the largest changes; up to 15 µGal. However, the reference stations have after this global match large gravity increases, twice the formal standard deviation of uncertainties. It also appears that the lowering of the zero level in 1988 still give negative mismatches in the central part of the field, while the mismatches have positive signs towards the rim. A level shift does not seem to fix all problems.

	78	**84**	**88**	**96**	**15**	**Average**
78		8.4	15.0	2.0	6.4	8.0
84	-8.4		6.6	-6.9	-3.2	-3.0
88	-15.0	-6.6		-12.5	-9.5	-10.9
96	-2.0	6.9	12.5		1.0	4.6
15	-6.4	3.2	9.5	-1.0		1.3

Table 55: Change in zero-level from using reference benchmarks to use a global model fit. Values are in µGal, with positive numbers meaning the "row" survey values are shifted to higher gravity.

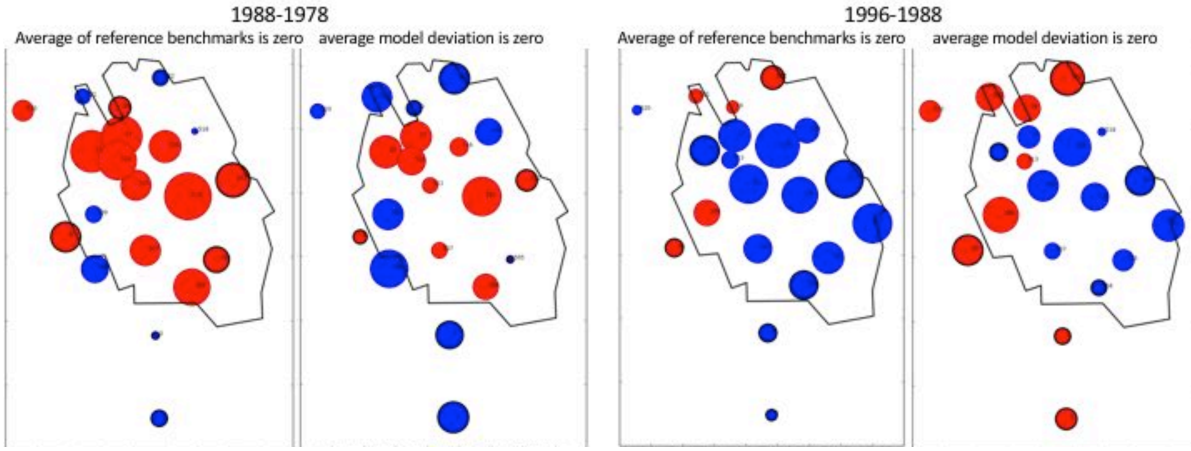

Figure 186: Difference maps of observed-modeled gravity changes 1988-1978 (left) and 1996-1988) right. For both time-lapse intervals have the zero-level been calculated in two different ways; left: average of reference benchmarks, right: average of model. Red means gravity decrease and blue gravity increase. Values are proportional to area of circle.

Cross-plots of observed and modeled gravity changes at stations inside the reservoir rim are shown in Figure 187. For the 1988-1978 differences, it appears as the observed time-lapse changes scales with the modeled changes by a factor of about 1.7, in addition to an intercept of 11 μGal. For the 2015-1978 differences is the scale factor 0.88 – insignificantly deviation from the expected value of 1. We have no explanation for a scaling factor different from 1, and why it should apply to particular surveys only.

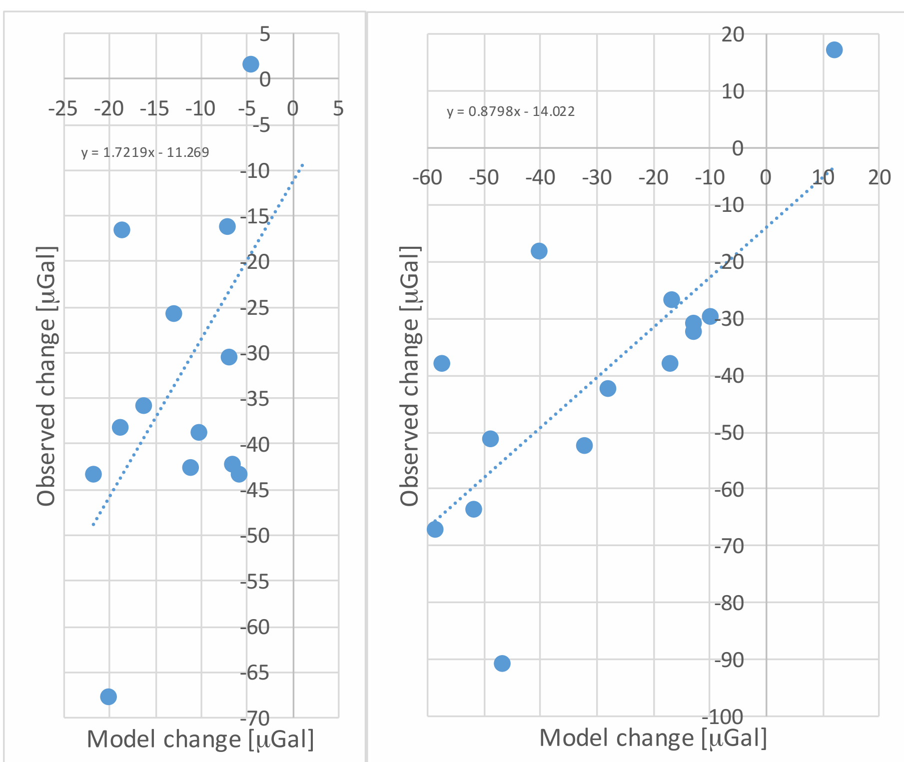

Figure 187: Cross-plot of observed and modeled gravity changes, after subsidence correction and using the reference stations to define zero level. Left: 1988-1978, right: 2015-1978.

Gravity change is cross-plotted against subsidence for 1988-1978 in Figure 188. After subsidence correction, there is a trend relating these (upper right plot in Figure 188). This can be expected in a gas depletion situation, in which subsidence and gravity will respond similarly. Stations #13 and 17 are outliers by showing relatively larger subsidence than gravity change. One cause of this could be that the subsidence values are 3-4 cm too high, which is less than 2 sigma of the expected depth uncertainty, and thus well possible. Another explanation for the outliers in the gravity-subsidence cross-plot could be that the reservoir is softer in this area than elsewhere. The lower plot in Figure 188 shows the deviation between observed and modeled gravity change vs. subsidence. Now there is a trend of opposite sign; increasing subsidence correlates with increasing gravity. The cause of this is not clear.

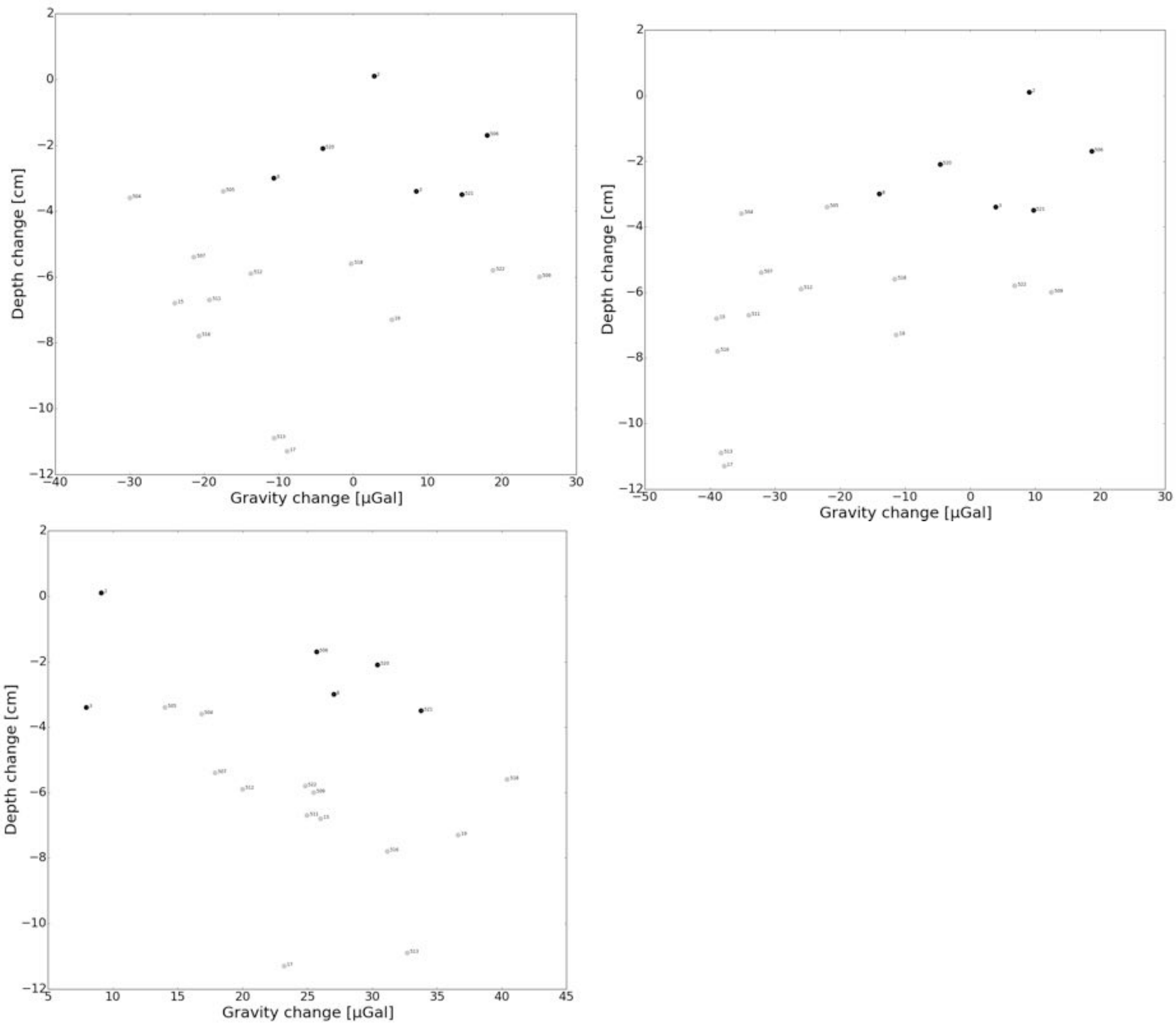

Figure 188: Cross-plot of gravity changes vs. subsidence, for the 1988 - 1978 time-lapse. Upper left: gravity change before subsidence correction, upper right: gravity change after subsidence correction, below: difference between observed and modeled gravity change.

From the known subsurface mass extraction from the underground (Figure 184 and Table 56, second data row), the area-integrated gravity change can be calculated, without knowledge of the detailed mass change distribution. With the current coarse grid of stations, we have calculated the average of all stations inside the rim of the field, and divided by the field area of 900 km^2 to represent the integral gravity value. The numbers are shown in Figure 189, where mass change and average gravity change are expected to be proportional. Also the volume of the subsidence bowl has been calculated as the average subsidence multiplied with field area. While the modelled gravity follows the mass change closely, the observed gravity deviates clearly in 1984 and 1988. Adjustment of the 1988 survey would require either i) a scale factor of 1/2.7 to all time-lapse gravity values, or ii) a shift in the zero-level of 19.5 µGal, iii) a shift in the subsidence of 6.3 cm (which means removal of the entire subsidence bowl, and is incompatible with the subsidence measurements), or a combination of these.

	1984-1978	1988-1978	1996-1978	2014/2015-1978
Total mass change [10^9 kg]	-226	-323	-488	-839
Gas production [10^9 kg]	-291	-427	-662	-1170
Water inflow [10^9 kg]	65	104	174	331
Areal gravity change [10^3 Gal m^2]	-18.1	-25.2	-18.6	-36.3
Modelled areal gravity change [10^3 Gal m^2]	-7.2	-10.2	-15.5	-27.0
Subsidence bowl [m^3]	40.5	58.4	78.4	160.1
Required zero-level shift [µGal]	-12.1	-19.5	-3.4	-10.4

Table 56: Key scalars through the production history since year 1978. Mass changes are provided by NAM.

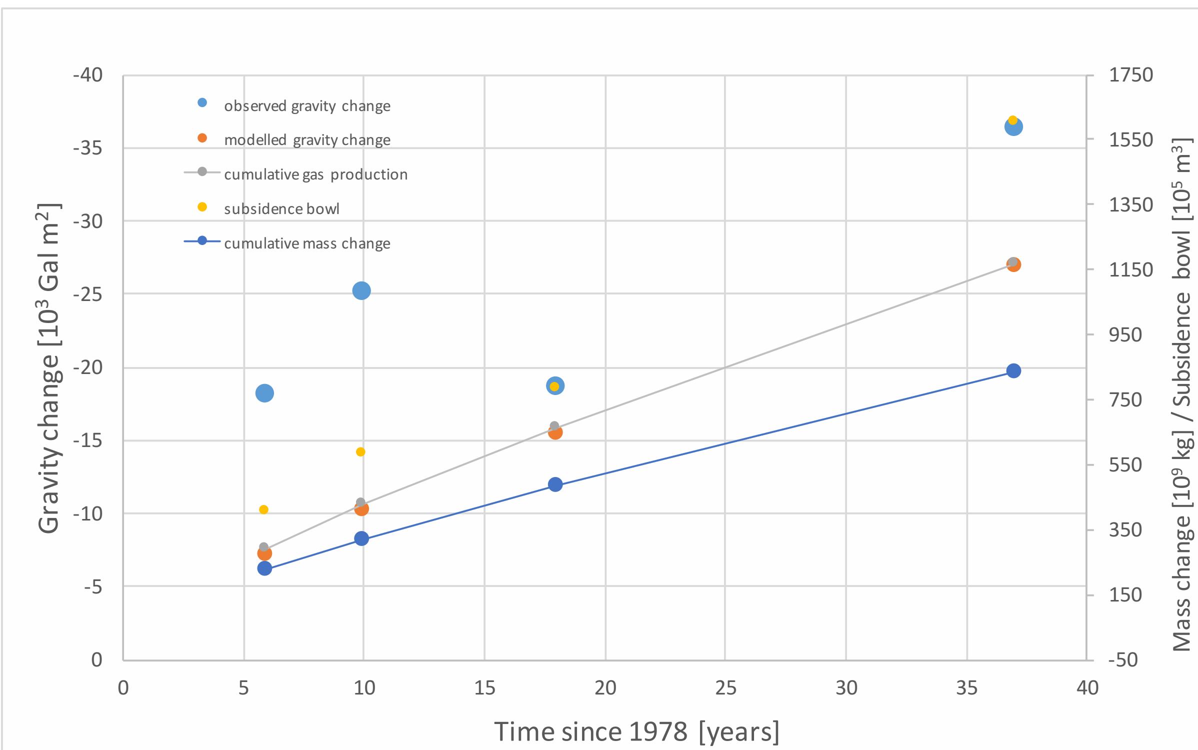

Figure 189: Plot of the scalars in Table 56. Mass changes and subsidence bowl have values shown on the right y-axis.

Station #2 Gasselte was used as reference in the three first surveys, and received 27, 21 and 16 visits, respectively. The intra-survey station error is therefore much less on this station than others. Deviation from the mean of all reference stations are shown in Table 57. One cause of these mis-matches can be the fluctuation in ground water level documented at Gasselte (page 136). The residuals 1984-1978 and 1988-1978 are both positive. This means that referencing the zero-level to

#2 instead of the average of all reference stations would increase the discrepancies in Figure 189 for the 1984 and 1988 surveys. We use the zero-level as defined by the reference stations in the further analysis.

	1984-1978	1988-1978	1996-1978	2015-1976
Residual [µGal]	2.0	8.3	-1.0	(16.7)

Table 57: Time-lapse gravity residuals at station #2 Gasselte; measurement – model, after subsidence correction and defining zero-level from all reference stations.

17.6 QC and editing of time-lapse values

We worked through all values and their consistency in time and space, as observations and and deviations from the modeled changes. The three most deviation values are:

1. #10 in 1988 seems about 25 µGal too low compared to other times and neighboring stations.
2. The 2015 value at station 18/518 is reduced by 30-40 µGal more than any other station and deviates >60 µGal from the model.
3. Station #20 had only one visit in 1984 (mmt 66). That measurement may be edited out.

The measurements were kept in the final data to be delivered, but left out of the further analysis and plots in this report.

17.7 Time-lapse results

Gravity changes over the entire period 2015-1978 are shown in Figure 190, before and after subsidence correction. In the uncorrected data there are about as many positive as negative observations of changes; mostly increases in the north and decreases in the south. After correcting for subsidence (Figure 190, right side), all values inside the rim are negative except one. This general picture is expected from gas depletion and mass reduction in the reservoir, and agrees with the scalar values shown in Table 56 and Figure 189.

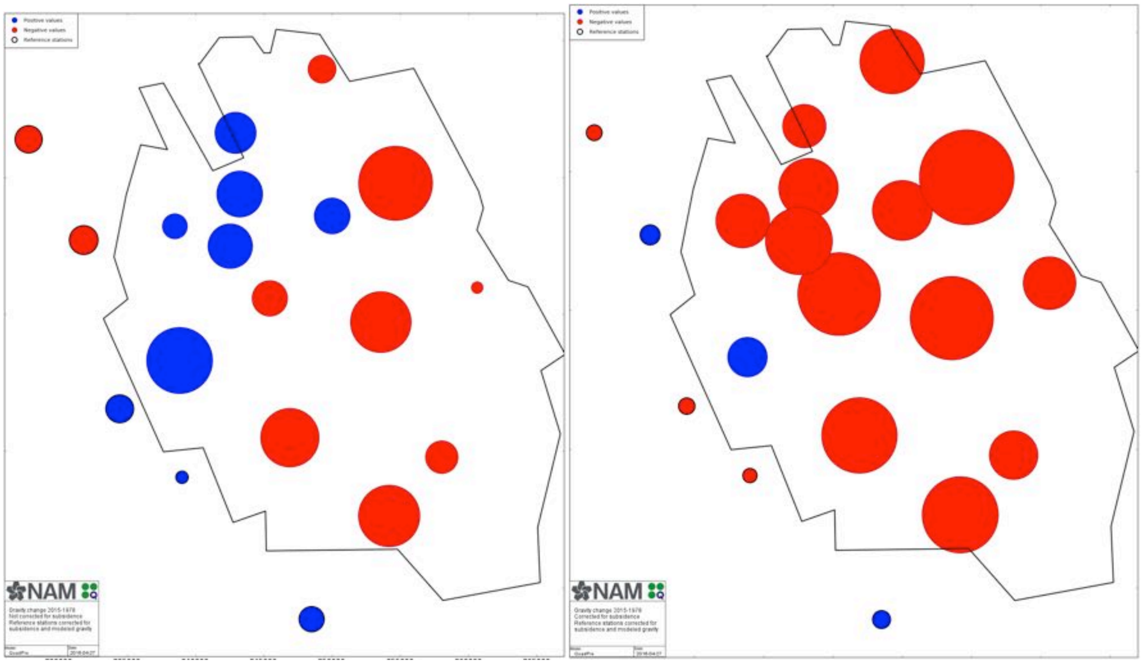

Figure 190: Gravity change 2015-1978, without and with subsidence correction (left and right). Blue are positive numbers, meaning a gravity increase with time. Signal is proportional to circle area. Reference benchmarks corrected for subsidence and modeled gravity changes are used as zero-level reference.

Gravity changes between 1996 and 2015 are shown in Figure 191. In the uncorrected data, there is a majority of negative changes. After subsidence correction, all stations except #9 are negative, as for the 2015-1978 range.

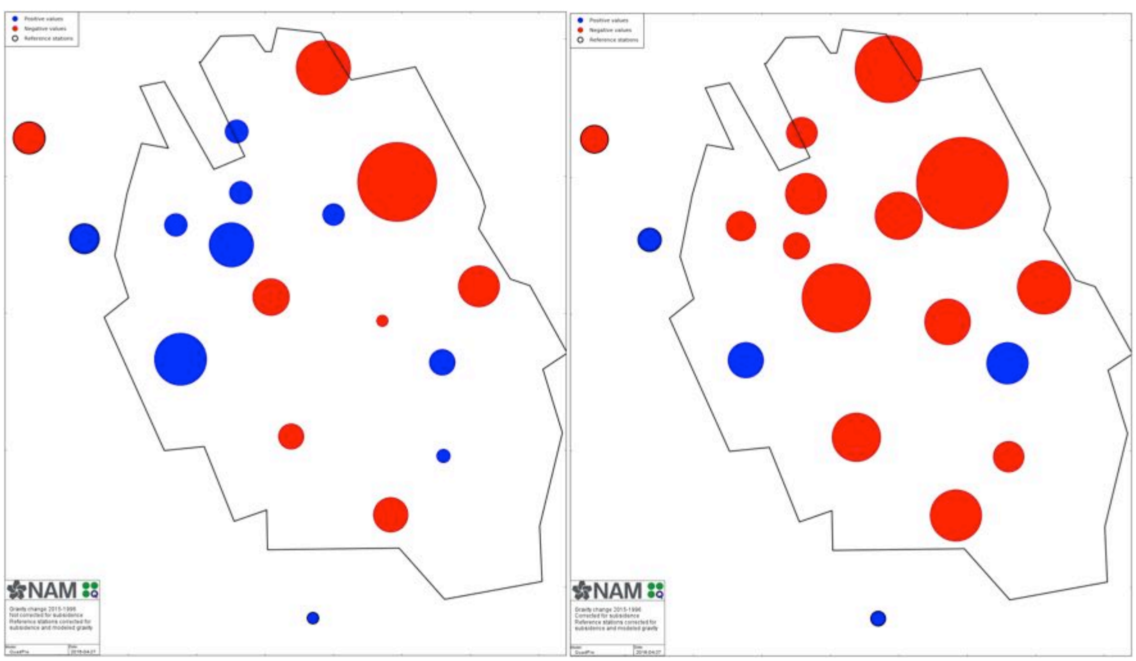

Figure 191: Gravity change 2015-1996, without and with subsidence correction (left and right). Blue are positive numbers, meaning a gravity increase with time. Signal is proportional to circle area. Reference benchmarks corrected for subsidence and modeled gravity changes are used as zero-level reference.

Gravity changes 2015-1996 after subsidence correction are compared against the modeled changes in Figure 192. Station 9 has a gravity increase in both the data and the model. Stations 11 and 12 have more than 30 µGal larger decrease in the data, which seems to be significant observations above the noise level. Station #34 has larger uncertainties, due to the change in observation height at the OM (page 98), and the 30 µGal increase should not be given much weight. The observation point could be edited away.

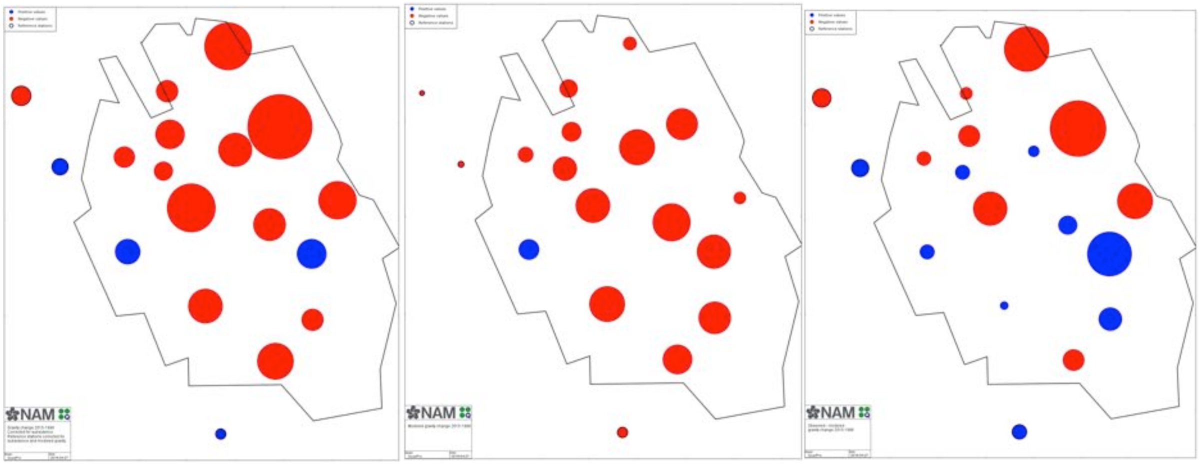

Figure 192: Gravity change 2015-1996; after subsidence corrections (left), model (middle) and data minus model (right). Signal is proportional to circle area. Reference benchmarks corrected for subsidence and modeled gravity changes are used as zero-level reference.

Gravity changes from 1978 to 2015 (after subsidence correction) are compared against the modeled changes in Figure 193. Data and model generally match well over most of the area. Station 9 shows gravity increase in both the data and the model. The largest deviations with some spatial consistency is at stations 13, 15 and 17, all with 17-20 µGal larger observed than modelled gravity reduction.

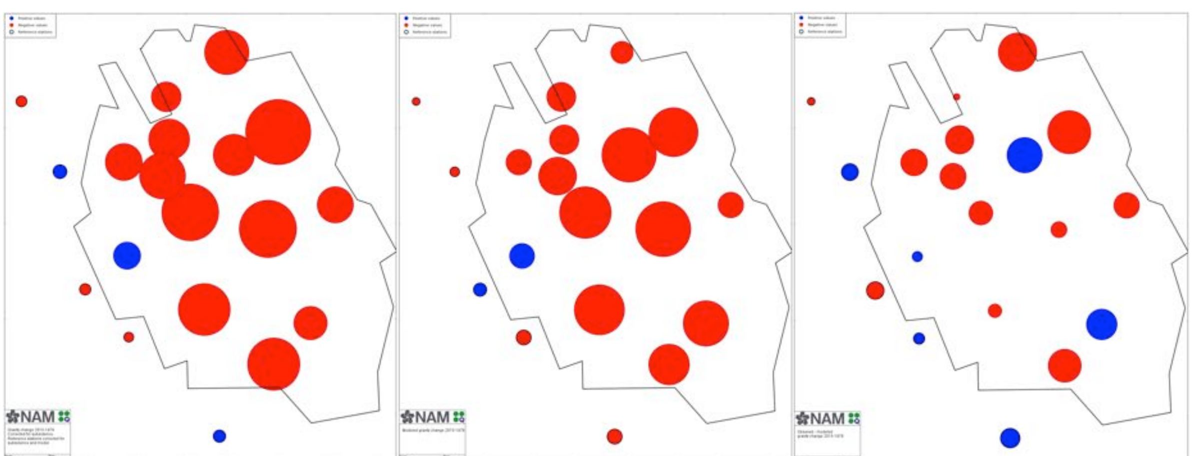

Figure 193: Gravity change 2015-1978; after subsidence corrections (left), model (middle) and data minus model (right). Signal is proportional to circle area. Reference benchmarks corrected for subsidence and modeled gravity changes are used as zero-level reference.

Gravity changes in consecutive periods are shown in Figure 194. Dominantly gravity decreases in the two first periods over the reservoir are followed by a clear gravity increase from 1996-1988.

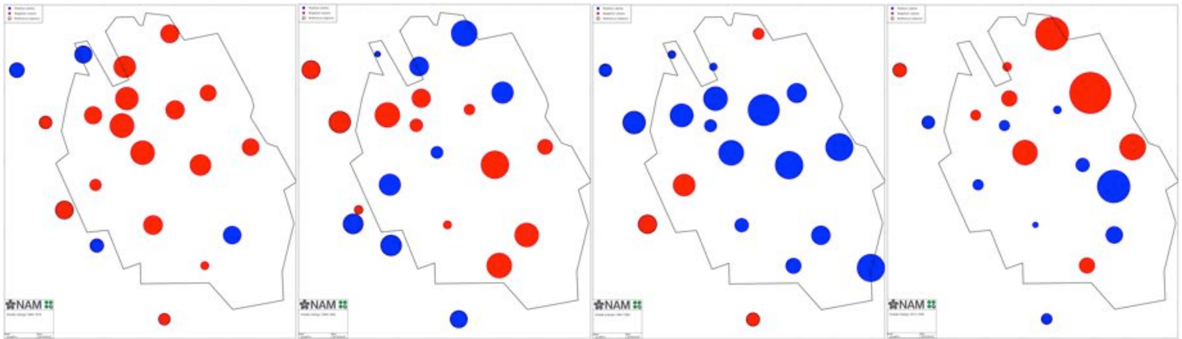

Figure 194: Gravity changes after subsidence corrections, from left to right: 1984-1978, 1988-1984, 1996-1988, 2015-1996. Signal is proportional to circle area. Reference benchmarks corrected for subsidence and modeled gravity changes are used as zero-level reference.

The zero-level may be set to match the model for all data, instead of using the reference stations only. This is shown in Figure 195 for 2015-1978. The #13, 15 and 17 mis-match is a bit reduced, and the positive mis-match at #5 and 16 slightly increased.

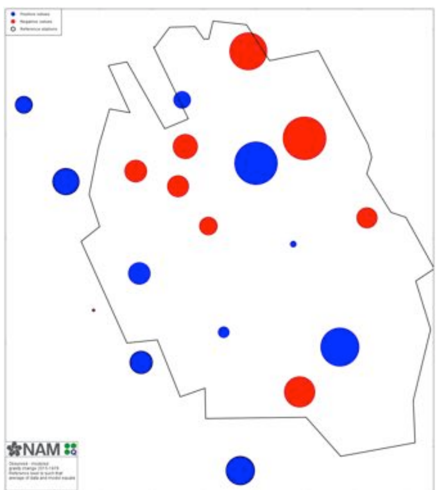

Figure 195: Gravity change 2015-1978; data minus model. Zero-level is now set such that all data average to zero.

Gravity changes 1996-1978 are shown in Figure 196. Two 3-station clusters of similar deviations are seen: Data exceeds the model at #13, 15 and 17, while the data show less change than the model at #11, 16 and 18.

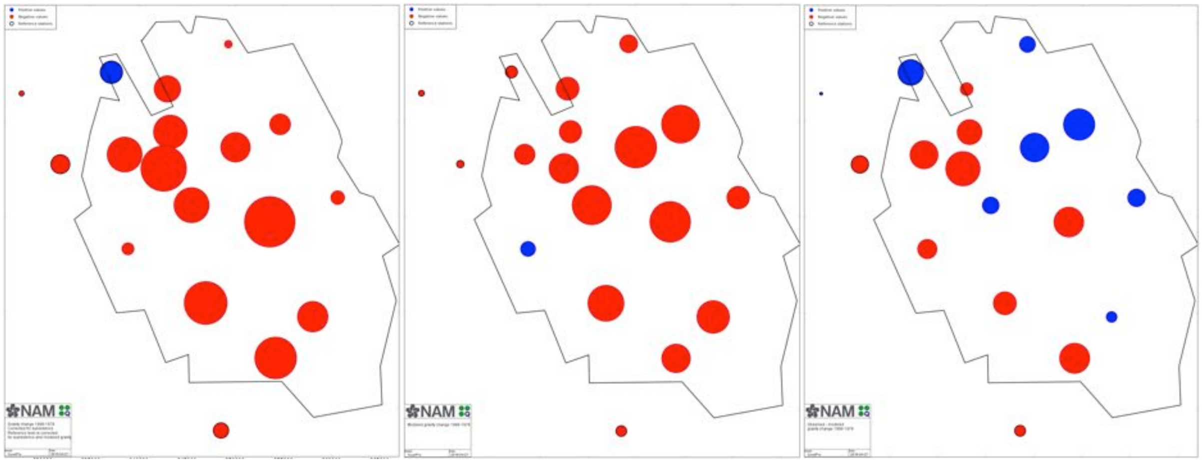

Figure 196: Gravity change 1996-1978; after subsidence corrections (left), model (middle) and data minus model (right). Signal is proportional to circle area.

Further look into single stations and trends are left to the interpretation phase.

17.8 Time-lapse uncertainties

Specific uncertainties may be assigned with each station and year. Additional uncertainties may be assigned with time-lapse differences if uncorrected changes occurred between surveys. Errors in the zero-level are affecting all stations equally in a survey-pair, while a scale factor error is proportional to gravity at a station.

The scatter in the data, and particularly the deviation from modeled changes, are indicators of the uncertainty level. This has been discussed for the reference stations on page 148; the data indicates a time-lapse noise level of about 9 μGal standard deviation. RMS values of the model matches of all stations inside the reservoir, for all time-lapse pairs, is shown in Table 58. Average mis-match is about 14 μGal. Both noise and model errors contribute to this number, which may be compatible with the 9 μGal for the noise, if the contributions from noise and model errors are about equal.

	78	**84**	**88**	**96**	**15**	**Average**
78		10.2	16.4	13.0	12.7	13.1
84	10.2		14.0	13.8	11.7	12.4
88	16.4	14.0		16.5	15.6	15.6
96	13.0	13.8	16.5		13.4	14.2
15	12.7	11.7	15.6	13.4		13.4

Table 58: RMS values of observation-model for stations inside the field, for all station pairs.

Station uncertainties in individual surveys are estimated in Table 59. Most of the pre-2015 values are 7 μGal, which gives 10 μGal in a time-lapse difference with another survey. Survey average repeatabilities are somewhat lower (Chapter 14), but additional time-lapse uncertainties arise from ground water variations, imperfect subsidence correction, and possibly other causes. Time-lapse differences involving the 2015-data have additional uncertainties related to transfer of station gravity values. These uncertainties are estimated in Table 36, and the values are inserted in next rightmost column in Table 59. For stations with no transfer of gravity values to a new site, but with altered surface conditions since 1996 (applies to #5, #9, #13 & #22), an extra 5 μGal uncertainty is related to uncertainty in the height change correction and in the density estimate of the material in-between old and new height. The columns of uncertainty in Table 59 are considered uncorrelated, and can thus be combined in a RMS sense to obtain final time-lapse station uncertainties.

No	Station name	1978	1984	1988	1996	Site transfer	2015 total
2	Gasselte church	7	7	7	7	-	Omitted
3	Annerveen	7	7	7	7	-	7
4 / 504	Tussenklappen	7	7	7	7	7	10
5	Roode Til	7	7	7	7	5	9
6 / 506	Haren	7	7	7	Omitted	5	9
7 / 507	Kooipolder	7	7	7	7	7	10
8	Groningen Sint Fraciscuskerk	7	7	7	Omitted	-	7
9	Ten Boer	7	7	7	7	5	9
10 / 510	Schildmeer	7	7	7	7	9	11
11 / 511	Ten Post	7	7	7	7	14	16
12 / 512	Delfzijl	7	7	7	7	9	11
13	Stedum	7	7	7	7	5	9
14 / 514	Winsum	7	7	7	7	13	15
15	Middlestum church	7	7	7	7	-	7
16 / 516	Leermens	7	7	7	7	14	16
17	Garsthuizen Garage	7	7	7	7	5	9
18 / 518	Bierum	7	7	7	7	8	11
19	Uithuizermeeden church	7	7	7	7	5	9
20 / 520	Eenrum	7	7	7	7	8	11
21 /521	Usquert	7	7	7	7	9	Omitted
22	Uithuizermeeden	7	7	7	7	5	9
30	Groningen NS		7	7	7	20	Omitted
33	Assen NS		7	7	7	20	Omitted
34 / 534	Wagenborgen OM				7	20	21
35 / 535	Gasselte OM				7	20	Omitted

Table 59: Estimated station uncertainties (standard deviation).

Zero-level uncertainty is estimated at 5 μGal or below, based on the scatter between observations and model at the reference stations (Table 53 and Table 54). When comparing all data (also inside the reservoir) with the model, best fits are obtained with zero-levels deviating up to 15 μGal from the level using reference stations (Table 55) – most for the 1988-survey. This could be due to either true zero-level errors or some other effects we have not been able to explain. We maintain 5 μGal as standard deviation for all zero-level uncertainties.

Scale factor uncertainty is estimated at about 3.3×10^{-4}, based on mis-match between the Monschau absolute tie and the Westerbork-Overschild-Aurich tie, and also the mis-matches of all time-lapse relative calibrations and ties to the Maastricht and Zwolle sites (Chapter 9 and Chapter 11). A comparison of increasing or decreasing the scale factor in 1978 with about 2.5×10^{-4} is shown in a data-model comparison of 1988-1978 in Figure 197. The stations of largest deviations (#10, 13, 15 and 17) have decreased the mis-match by about 4 μGal (8-12 %) in the last case, only capable of explaining a small portion of the mis-match.

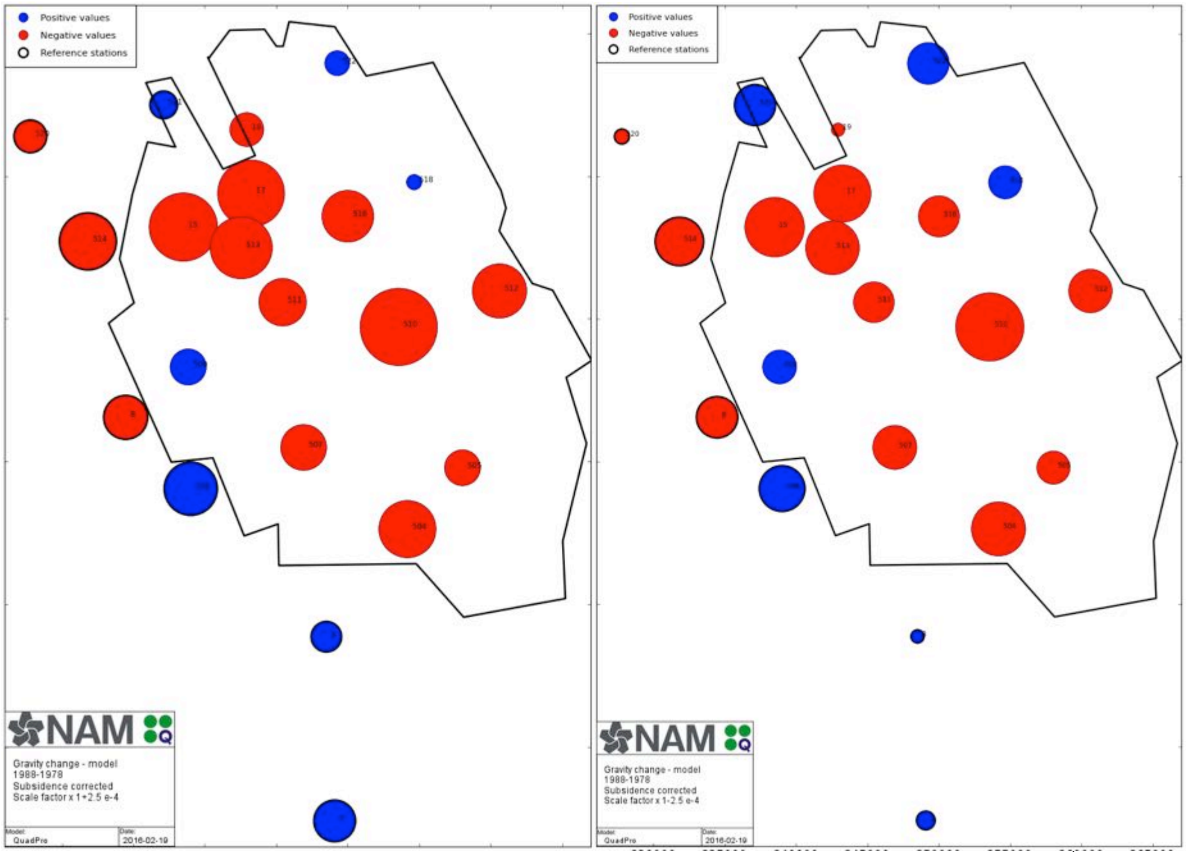

Figure 197: Gravity change - model 1988-1978, with scale factor in 1978 increased by 2.5 × 10^{-4} (left) and decreased by 2.5 × 10^{-4} (right).

17.9 Comparison with previous processing

Our results can for the pre-2015 surveys be compared with those of Bilker (1996), where subsidence-corrected gravity changes are listed in Table 5.10 (page 49 in Bilker 1996). There are significant changes in zero-level, or average values, in the two processed versions, as listed in Table 60. Values are all positive, meaning that the zero-level is defined higher in the old processing, causing larger gravity reductions over the field. This would increase the mis-match even more than we see in the current version. In the 1996-processing, all stations were referenced to #2 Gasselte.

	78	**84**	**88**	**96**
78		8.8	24.7	27.2
84			14.6	20.2
88				3.8
96				

Table 60: Zero-level variations between the 2016-processing to 1996-processing, in µGal.

Comparison of single station values between 1996- and 2016-processing after the zero-level discrepancies have been taken out are shown in Figure 198. For the 1988-data, a scale factor variation gives a north-south trend in the residuals. For the 1996-1978 difference, a northwestern area of negative changes is observed, and the cause of this is not clear. RMS differences are 8.6, 10.8 and 8.4 µGal for the three comparisons.

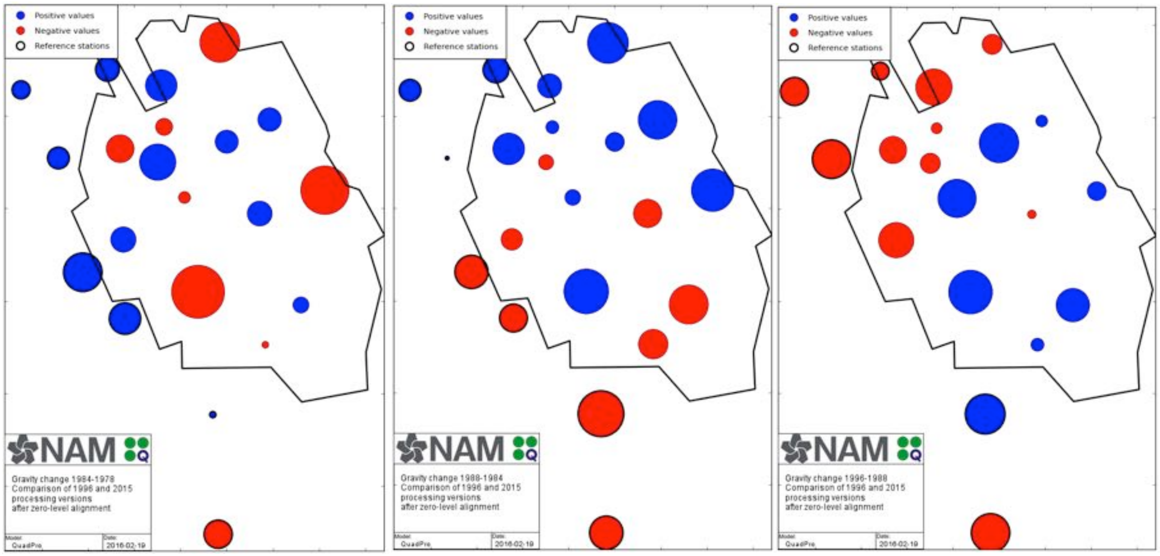

Figure 198: Comparison of time-lapse gravity from 1996-processing (Bilker) and the current. Left: 1984-1978, middle: 1988-1984, right 1996-1988.

18 Conclusions

The 2015 gravity data at 98 stations show, after final processing, an estimated intra-survey measurement repeatability (standard deviation) of 1.7 μGal and average station uncertainty of 1.1 μGal. This is significantly better than the target measurement repeatability of 4 μGal, and probably the most accurate land gravity survey made to date. The continuous day-night measurements, avoidance of large temperature fluctuations and the use of three sensors with continuous recoding of raw data have probably all contributed to the good result.

Reprocessing of the four earlier vintages have lowered their station uncertainties somewhat compared to the earlier analysis; from 4-7 μGal and down to 3-5 μGal. This may be due to better drift and earth tide corrections.

Two reference gravimeters agree with the tide model within 1 μGal, and indicate the current model is not a limiting factor for the final precision. Various scale factor calibrations show discrepancies of up to 3.3×10^{-4}, which is larger than the formal uncertainties of each calibration. The reasons for this remains unclear.

Although a large amount of ground water data exists, hydrology gravity corrections have not been applied to the final data, because of insufficient confidence in the method of calculation. Corrections are likely to be below 10 μGal, and likely not alter the final results in this report dramatically. Better hydrology corrections will be increasingly important in future monitoring because of higher measurement precision. This will require better understanding of the moisture and water transport through the soil, and further work on ground water and the gravity corrections is recommended to be initiated well before a next monitoring survey.

Uncertainties in the provided height data are estimated at 1.5 cm, transforming to a 6.5 μGal time-lapse gravity uncertainty. Time-lapse results are consistent with a noise level of about 9 μGal (standard deviation) on average, somewhat higher than the intra-survey repeatabilities. Additional time-lapse error sources are mass changes locally at the stations and in the ground water/soil moisture. Larger than predicted gravity decreases over the field 1984-1978 and 1988-1984 are well above the uncertainties, and lack an explanation. Observed gravity decreases 1978–1996–2015 are for some stations significantly larger than model predictions, with further analysis left to the interpretation phase.

19 Recommendations for future work and surveys

It will continue to be challenging to keep track of physical changes at the stations, as it was over the 19 years' time-span since 1996. We recommend to check the status of all locations regularly, by visits and photo documentation at about 2 year intervals. Each round of inspections could be done by one person in a car, visiting about 15-20 stations per day and requiring about 5-7 normal working days for covering the 98 station grid.

The influence of ground water and soil moisture variations on gravity is well known, but better quantitative knowledge of the mechanisms at Groningen would improve the precision of the corrections. This could be obtained by a more thorough analysis of the historical data on water level in the canals and ditches, rainfall and soil conditions, available from the Watershap's and the Geological Survey of the Netherlands database (Dinoloket). Based on this large database, improved methods could be developed. In future surveys, additional hydrology measurements could potentially be done at the stations, by the gravity crew. This will require some time for development of new and inexpensive technology, like hand-held probes that can penetrate 1-2 m deep with human force. Improved precision of hydrology corrections will be particularly important in order to utilize the high precision of the 2015-survey and future surveys.

The precision of tidal models could be further investigated by acquiring months-long undisturbed gravity records, with a superconducting or low-drift Lacoste-Romberg gravimeter. As the current analysis suggest the tide model has an accuracy of 1 μGal or better, this would be a lower-priority investigation.

The subsidence data from 1978 to 1996 contributes significantly to the total uncertainties, and we recommend to work more carefully through the data and uncertainty assessments. Geomechanical modelling, which has been done or is to be done, could possibly contribute to those assessments. Improved precision of height measurements in future surveys can significantly increase precision of the further gravity monitoring, and ways to obtain that should be investigated.

Maximum observed gravity rates of change at the central parts of the field have been about -1.5 μGal/year. With the same station uncertainty in a next survey as in 2015, and with no additional time-lapse uncertainties, the uncertainty in the time-lapse difference may be 1.6 μGal. Uncertainties in the height measurements and subsidence correction may be about 1 cm, corresponding to 3 μGal, and be the dominating source in the total error of 3.4 μGal. The time-lapse gravity changes caused by gas extraction are likely to exceed a 3.4 μGal noise level after less than 3 years. We recommend to acquire a next survey after 3-4 years. With shorter time-gaps, the possibilities of sorting out other sources of time-lapse noise, such as hydrology variations, shallow (peat) compaction and other local mass changes near the surface, will increase. We recommend, from a geophysical point of view, to acquire a new survey in 2018 or 2019.

20 References

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21 Appendix A: Survey deliverables

The following files are delivered on an external hard-drive:

1. Calibration data
   a. Scale factor Monschau-Westerbork
   b. Scale factor Maastricht-Gasselte
   c. Tilt September 10th
   d. Tilt September 12th
   e. Tilt September 17th
   f. Tilt September 30th
   g. Transfer values at 11 stations
2. Environmental data
   a. Weather at Eelde in pre-2015 surveys (Excel)
   b. 2015
      - Weather Groningen (Excel)
      - Operators logbook (two volumes)
      - Temperature in van and on top of gravimeter (two csv-files)
3. Station data
   a. Station coordinates (Excel)
   b. Pictures, in 98 subdirectories
4. Raw survey gravity data
   a. 1978: 114 files
   b. 1984: 142 files
   c. 1988: 110 files
   d. 1996: 173 files
   e. 2015: 927 files
5. Final report (pdf-format)
6. Station values of gravity: best estimates and uncertainties for all surveys (Excel)
7. Time-lapse gravity changes: best estimates and uncertainties for all survey pairs (Excel)

22 Appendix B: Details of the absolute gravity measurement in Overschild

22.1 Information from the ‘set file’ and absolute value of gravity per set at floor level

Set	Time	DOY	Year	Gravity	Sigma	Error	Uncert
1	0,7870486111	259	2015	981339107,547	44,015	3,128	4,886
2	0,8286921296	259	2015	981339106,610	64,960	4,617	5,949
3	0,8703587963	259	2015	981339094,645	100,687	7,120	8,048
4	0,9120254630	259	2015	981339108,509	97,928	7,031	7,970
5	0,9536805556	259	2015	981339116,957	78,683	5,578	6,723
6	0,9953125000	259	2015	981339097,214	3481,692	248,692	248,721
7	0,0370254630	260	2015	981339121,130	497,955	35,211	35,410
8	0,0786921296	260	2015	981339112,599	174,577	12,344	12,902
9	0,1203819444	260	2015	981339120,951	156,145	11,097	11,714
10	0,1620138889	260	2015	981339099,593	100,147	7,099	8,030
11	0,2036921296	260	2015	981339107,853	138,558	9,822	10,515

Set	Tide	Load	Baro	Polar	Transfer	Refxo	Temp	Pres	Accept	Reject
1	-75,071	-1,142	-7,259	-3,34	393,148	-0,002	337,466	989,204	198	2
2	-65,982	-0,602	-7,238	-3,34	393,148	-0,002	337,515	989,273	198	2
3	-48,221	0,077	-7,210	-3,34	393,148	-0,002	337,591	989,368	200	0
4	-25,333	0,724	-6,988	-3,34	393,148	-0,002	338,161	990,106	194	6
5	-2,120	1,178	-6,969	-3,34	393,148	-0,002	338,203	990,168	199	1
6	16,519	1,330	-6,997	-3,34	393,148	-0,002	338,138	990,075	196	4
7	26,804	1,146	-7,035	-3,34	393,148	-0,002	338,066	989,950	200	0
8	26,828	0,681	-7,002	-3,34	393,148	-0,002	338,118	990,060	200	0
9	17,068	0,059	-6,981	-3,34	393,148	-0,002	338,197	990,129	198	2
10	0,151	-0,556	-6,913	-3,34	393,148	-0,002	338,357	990,355	199	1
11	-19,923	-1,005	-6,771	-3,34	393,148	-0,002	338,706	990,829	199	1

Table 61: Information per set taken from the 'set file'. Note that the column 'Gravity' shows the absolute value of gravity at floor level.

22.2 ‘Project file’, which contains the setup data of the FG5

```
Micro-g Solutions g Processing Report
File Created: 09/23/15, 09:53:11

Project Name: Overschild_Groningen_16_17_9_2015
g Acquisition Version: 4.041600
g Processing Version: 7.070307

Company/Institution:
Operator: RHCR

Station Data
Name: Overschild_16_17_sept_2015
Site Code: 1
Lat:  53.28239 Long:    6.78433 Elev:   -1.30 m
Setup Height: 13.03 cm
Transfer Height:  0.00 cm
Actual Height: 129.41 cm
Gradient: -3.038 µGal/cm
Nominal Air Pressure: 1013.40 mBar
Barometric Admittance Factor:  0.30
```

Polar Motion Coord: 0.2242 " 0.3435 "
Earth Tide (ETGTAB) Selected
Potential Filename: C:\Program Files\Micro-g Solutions Inc\gWavefiles\ETCPOT.dat
Delta Factor Filename: C:\gData\Overschild_Groningen\OceanLoad-Overschild_16_17_sept_2015.dff
Delta Factors

Start	Stop	Amplitude	Phase	Term
0.000000	0.002427	1.000000	0.0000	DC
0.002428	0.249951	1.160000	0.0000	Long
0.721500	0.906315	1.154250	0.0000	Q1
0.921941	0.974188	1.154240	0.0000	O1
0.989049	0.998028	1.149150	0.0000	P1
0.999853	1.216397	1.134890	0.0000	K1
1.719381	1.906462	1.161720	0.0000	N2
1.923766	1.976926	1.161720	0.0000	M2
1.991787	2.002885	1.161720	0.0000	S2
2.003032	2.182843	1.161720	0.0000	K2
2.753244	3.081254	1.07338	0.0000	M3
3.791964	3.937897	1.03900	0.0000	M4

Ocean Load ON, Filename: C:\gData\Overschild_Groningen\OceanLoad-Overschild_16_17_sept_2015.olf

Waves:	M2	S2	K1	O1	N2	P1	K2	Q1	Mf	Mm	Ssa
Amplitude (µGal):	0.987	0.398	0.212	0.070	0.238	0.066	0.101	0.023	0.000	0.000	0.000
Phase (deg):	41.5	21.4	51.4	137.1	73.0	50.7	17.0	-171.0	0.0	0.0	0.0

Instrument Data
Meter Type: FG5
Meter S/N: 234
Factory Height: 116.38 cm
Rubidium Frequency: 10000000.00357 Hz
Laser: WEO100 (219)
ID: 632.99117754 nm (0.18 V)
IE: 632.99119473 nm (-0.33 V)
IF: 632.99121259 nm (-0.76 V)
IG: 632.99123023 nm (-1.20 V)
IH: 632.99136890 nm (-1.88 V)
II: 632.99139822 nm (-1.68 V)
IJ: 632.99142704 nm (-1.52 V)
Modulation Frequency: 8333.300 Hz

Processing Results
Date: 09/16/15
Time: 23:53:19
DOY: 259
Year: 2015
Time Offset (D h:m:s): 0 0:0:0
Gravity: 981339107.63 µGal
Set Scatter: 5.88 µGal
Measurement Precision: 1.77 µGal
Total Uncertainty: 4.15 µGal
Number of Sets Collected: 11
Number of Sets Processed: 11
Set #s Processed: 1,2,3,4,5,6,7,8,9,10,11
Number of Sets NOT Processed: 0
Set #s NOT Processed:
Number of Drops/Set: 200
Total Drops Accepted: 2181
Total Drops Rejected: 19
Total Fringes Acquired: 700
Fringe Start: 19
Processed Fringes: 601
GuideCard Multiplex: 4
GuideCard Scale Factor: 250

Acquisition Settings
Set Interval: 60 min

Drop Interval: 5 sec
Number of Sets: 11
Number of Drops: 200

Gravity Corrections
Earth Tide (ETGTAB): -13.57 µGal
Ocean Load: 0.17 µGal
Polar Motion: -3.34 µGal
Barometric Pressure: -7.03 µGal
Transfer Height: 393.15 µGal
Reference Xo: -0.00 µGal

Uncertainties
Sigma Reject: 3.00
Earth Tide Factor: 0.000
Average Earth Tide Uncertainty: 0.00 µGal
Ocean Load Factor: 0.00
Average Ocean Load Uncertainty: 0.00 µGal
Barometric: 0.00 µGal
Polar Motion: 0.00 µGal
Laser: 0.00 µGalClock: 0.00 µGal
System Type: 0.00 µGal
Tidal Swell: 0.00 µGal
Water Table: 0.00 µGal
Unmodeled: 0.00 µGal
System Setup: 0.00 µGal
Gradient: 3.75 µGal (0.03 µGal/cm)

Comments

23 Appendix C: Daily reports

23.1 September 5th

1. Ongoing activity
Mobilization (Joel White and Ola Eiken) / travel to Groningen (Mark Zumberge)
2. HSE
Joel White and Ola Eiken passed yesterday Shell's exam for Life Saving Rules and got their NAM passes.
BVCA exams are scheduled for Monday 7th at 15:00 in Rotterdam for Joel, Mark and Ola (not confirmed yet).
BVCA exams are scheduled for Wednesday 9th at 19:00 in Ten Boer for the rest (specific location to be found).
3. Activities last 40 hours
Established head quarter in Hotel de Pleisterplaats, Ten Boer.
Established workshop in garage, Ten Boer.
Gravimeters were put on heat about 19:00 Thursday.
Visit to gravity bunker in Westerbork (Joel White and Ola Eiken), and pick up of key for unlimited access the next 3 1/2 weeks.
Kickoff meeting with NAM (Wim van der Veen).
Picked up survey car at KAF Autoverhuur.
Gathering of additional site information for the scale factor calibration survey.
4. Planned activities next 24 hours
Continue mobilization in Ten Boer.
Prepare survey car.
Pick up VW Caddy.
Mark Zumberge will arrive Groningen around noon.
Calibration survey planned to start Sunday morning. Both end sites; in Westerbork and Monschau, got cleared Friday. Site photographies for the sites Zwolle NS and Maastricht NS were made available by Marc Crombaghs. Still uncertainties in site descriptions for the NEDZWA 93/99 sites that were visited in Groningen 1984, 1988 and 1978 gravity campaigns, and priority will be given to the Westerbork and Monschau sites for this calibration.
5. Overall progress
Mobilizing as planned.
6. Accuracy of measurements
N/A
7. Long-term forecast
BVCA exam on Monday for Joel, Mark and Ola will defer gradient measurements at NAM sites to later in the week.
The plan for training and meetings Wednesday-Friday next week, and survey startup Saturday 12th remains unchanged.
8. Weather forecast next 24 hours
12-17 oC, light showers, breeze
9. Areas of concern
Practicalities around BVCA exams.
Site clearance and descriptions; several remain yet.

23.2 September 6th

1. Ongoing activity
Scale factor calibration survey (Joel White and Mark Zumberge)
2. HSE
None
3. Activities last 24 hours
Mobilization
Preparing survey car
Mark Zumberge arrived 13:45
4. Planned activities next 24 hours
Calibration measurements in Westerbork, Zwolle (possibly), Monschau and Westerbork again, expected to take about 10 hours (Joel and Mark).
Scouting in the survey area (Ola)
5. Overall progress
Mobilizing as planned.

6. Accuracy of measurements
N/A
7. Long-term forecast
BVCA exam on Monday for Joel, Mark and Ola will defer gradient measurements at NAM sites to later in the week.
The plan for training and meetings Wednesday-Friday next week, and survey startup Saturday 12th remains unchanged.
8. Weather forecast next 24 hours
12-16 oC, showers, breeze
9. Areas of concern
Practicalities around BVCA exams.
Site clearance and descriptions; several remain yet.

23.3 September 7th

1. Ongoing activity
Safety courses
2. HSE
The guard at Westerbork notified police just after the evening measurement was completed. The police showed up during the drive out from Westerbork, and the situations was quickly clarified. The staff at the observatory had obviously not informed the guard about Quad's planned activities, but now the guard (and the police) should know that we are going to pay more visits during the coming three weeks.
3. Activities last 24 hours
Scale factor calibration survey:
9:15 Departure Ten Boer
10:35 Measurement, Westerbork
16:32 Measurement, Monschau
21:20 Measurement, Westerbork
22:30 Arrival Ten Boer
4. Planned activities next 24 hours
LSR, video, NAM-pass for Mark in Assen in the morning
BVCA exams are scheduled for Monday 7th at 15:00 in Rotterdam for Joel, Mark and Ola (not confirmed yet).
5. Overall progress
As planned.
Measurement in Zolle was skipped because of noisy conditions at the site. Site seemed unaltered when compared to the picture from 1999.
Absolute measurements by TU Delft has been deferred to next week; starting 14th September, due to availability of Rene Reudink.
6. Accuracy of measurements
Measurements not processed yet.
7. Long-term forecast
Gradient measurements when suitable in-between training Tuesday-Friday.
Survey startup Saturday 12th.
8. Weather forecast next 24 hours
15-18 oC, sunny, breeze
9. Areas of concern
Practicalities around BVCA exams.
Site clearance and descriptions; several remain yet.

23.4 September 8th

1. Ongoing activity
Initiate gradient measurements
2. HSE
None
3. Activities last 24 hours
LSR, video, NAM pass for Mark Zumberge
Site planning at NAM (Ola)
Picked up personal safety logbooks.
VCA exam for Joel, Mark and Ola in Rotterdam; all passed.

4. Planned activities next 24 hours
Gradient measurements at NAM-sites.
Arrival of Michael Davis and Tom Eirik Slettahjell
5. Overall progress
As planned.
6. Accuracy of measurements
Measurements not processed yet.
7. Long-term forecast
Gradient measurements when suitable in-between training Wednesday-Friday.
Survey startup Saturday 12th.
8. Weather forecast next 24 hours
13-18 oC, cloudy, breeze
9. Areas of concern
None

23.5 September 9th

1. Ongoing activity
Gradient measurements / mobilize crew.
2. HSE
None
3. Activities last 24 hours
Gradient measurements at Leermens an Bierum
Scouting on remaining gradient locations (Ola); new Schildmeer station is proposed relocated outside the fence.
Arrival of crew: Michael Davis and Tom Eirik Slettahjell.
4. Planned activities next 24 hours
Gradient measurements at Ten Post, Kooipolder and Delfzijl
Defensive driving course for 4 people
Arrival of Snorre Sulheim, Dave Jabson and Billy Hatfield
VCA exam for the rest of the crew tonight at 19:00 in Ten Boer
5. Overall progress
As planned.
6. Accuracy of measurements
Calibration survey records look good. Need to get absolute values confirmed at Delft and Brussels institutes before concluding on scale factor value. QC plots for individual measurements are attached.
7. Long-term forecast
Gradient measurements when suitable in-between training Wednesday-Friday.
Survey startup Saturday 12th.
8. Weather forecast next 24 hours
11-19 oC, sunny, breeze
9. Areas of concern
None

23.6 September 10th

1. Ongoing activity
Mobilize crew / safety training.
2. HSE
Mark Zumberge borrowed safety shoes from NAM at Hoogezand Tuesday and Wednesday. Delivered back Wednesday evening.
Crew talks of measurement procedures went along with the gradient measurements, to adjust and improve.
3. Activities last 24 hours
Gradient measurements at Ten Post and Kooipolder. 5 measurements at each location (two inside and three outside). The smaller van (WV Caddy was used, because the survey van was occupied by driving training.
Defensive driving training for Michael Davis, Ola Eiken, Joel White and Tom Eirik Slettahjell.
Arrival of crew: Billy Hatfield, Dave Jabson, Snorre Sulheim, Patrick Paitz.
VCA exam held in Ten Boer for remaining crew. All six passed.

4. Planned activities next 24 hours
Defensive driving course for 4 people
Permit to work training for crew leads – 4 people
LSR + NAM pass – 6 people
Improving procedure descriptions and setting up gPhone tidal gravimeter – Mark
Scouting with Shizhuo at new stations - Ola
5. Overall progress
About one day behind plan with respect to gradient measurements.
6. Accuracy of measurements
Nothing further to report since yesterday. First gradient measurements will be processed today.
7. Long-term forecast
Gradient measurements after kick-off meeting Friday. Not all stations will be finished Friday. Remaining gradient measurements may be done Saturday or after the main survey. We propose to spend Saturday 12th for gradient measurements, and start survey Sunday 13th.
8. Weather forecast next 24 hours
11-19 oC, sunny, breeze
9. Areas of concern
Progress for gradient measurements has been a bit slower than anticipated. We do not expect this to influence the survey, when coming up to full speed.

23.7 September 11th

1. Ongoing activity
Mobilize crew / safety training.
2. HSE
Safety training, see below.
All crew meeting at the hotel in Ten Boer 18:00-20:00, going through the job.
3. Activities last 24 hours
Work permit training for Joel White, Michael Davis, Billy Hatfield and Tom Eirik Slettahjell.
LSR + video + NAM pass for Rob Paesens, Ronald de Jong, Patrick Paitz, Tom Eirik Slettahjell, Snorre Sulheim, Michael Davis, Dave Jabson.
Defensive driving course for Snorre Sulheim, Dave Jabson, Patrick Paitz and Billy Hatfield.
All crew meeting at the hotel in Ten Boer 18:00-20:00, going through the job.
Setting up gPhone tidal gravimeter (Mark Zumberge)
Scouting at stations (Shizhuo Liu and Ola Eiken)
4. Planned activities next 24 hours
Kick-off meeting at NAM, Assen – all
Setting up survey vehicle with equipment.
Gradient measurements at 1-2 sites.
Data processing of caquired data.
5. Overall progress
About one day behind plan with respect to gradient measurements.
6. Accuracy of measurements
Nothing further to report since yesterday.
7. Long-term forecast
Gradient measurements will be done Saturday. This will also work as training of the crew. The round-the-clock survey will start Sunday 13th at 9:00.
Absolute measurements in OVerschild bu TU Delft is now scheduled for Wednesday-Thursday 16th-17th September.
8. Weather forecast next 24 hours
10-20 oC, sunny, breeze
9. Areas of concern
Several stations remain to be cleared for the survey.

23.8 September 12th

Ongoing activity
Gradient measurements

2. HSE
None
3. Activities last 24 hours
Kick-off meeting in Assen, all crew participated.
Survey vehicle set up.
Gradient measurements done at 12 Delfzijl and 4 Tusschenklap
4. Planned activities next 24 hours
Gradient measurements at 6 Haren and 20 Eenrum.
Start of regular survey tomorrow 9:00
5. Overall progress
According to revised plan
6. Accuracy of measurements
Nothing further to report since yesterday.
7. Long-term forecast
Absolute measurements in Overschild bu TU Delft is now scheduled for Wednesday-Thursday 16th-17th September.
8. Weather forecast next 24 hours
11-22 oC, partly cloudy, afternoon showers, breeze
9. Areas of concern
Stations remain to be cleared for the survey.

23.9 September 13th

1. Ongoing activity
Survey start
2. HSE
Toolbox talks before the gradient sites. Training of new people in measurement procedures.
3. Activities last 24 hours
Gradient measurements at 6 Haren and 20 Eenrum.
Visit to Overschild windmill before the first measurements (Mark and Ola)
Various preparations before survey start (all crew).
Tilt calibration.
Processing of records made to date.
Scouting at stations (Shizhuo Liu and Ola Eiken)
4. Planned activities next 24 hours
Measurements at 404 Overschild, 11 Ten Post, 123 Garrelsweer, 16 Leermens, 120 Biessum, 115 Krewerd, 18 Bierum, 162 Spijk, 105 Roodeschool, 101 Uithuizermeeded Dwarsweg, 104 Uithuizen Departementsstraat, 20 Eenrum, 403 Kloosterburen, 112 Warffum, 15 Middlestum Church, 113 Huizinge, 122 Stedum, 404 Overschild
5. Overall progress
8 gradient stations have been measured, 3 stations remain
6. Accuracy of measurements
Repeatability of transfer values is 1-2 uGal, with average of about 1.4 uGal. Time series look good
7. Long-term forecast
Continue regular surveying.
Absolute measurements in Overschild by TU Delft is now scheduled for Wednesday-Thursday 16th-17th September.
8. Weather forecast next 24 hours
15-22 oC, partly sunny, breeze
9. Areas of concern
Several stations remain to be cleared for the survey.

23.10 September 14th

1. Ongoing activity
Measurement at station 158 Veendam Church
2. HSE
Toolbox talks before each shift, and at each shift change in the field.
Three times persons have asked the crew about what they are doing. All friendly conversations, and the NAM information letter has been handed out.

3. Activities last 24 hours (until 8:00)
21 measurements at stations 404, 511, 123, 516, 120, 115, 18, 162, 105, 101, 104, 520, 403, 112, 113, 122, 404, 134, 139, 506, 402.
All measurements have gone well.
4. Planned activities next 24 hours
Measurements at 150 Veendam Church, 4 Tusschenklap, 156 Meeden, 5 Roode Til, 164 Oostwold Langeweg, 142 Nieuwolda kerkelaan, 304
Roode Til and Delfzijl are inside the NAM fence and will need help from a NAM person.
5. Overall progress
20 station measurements out of about 300; 7% completed
8 gradient stations out of 11
6. Accuracy of measurements
Time series look good. No repeats at Overschild yet.
7. Long-term forecast
Continue surveying.
Absolute measurements in Overschild by TU Delft is now scheduled for Wednesday-Thursday 16th-17th September.
8. Weather forecast next 24 hours
15-19 oC, cloudy, possible showers in the afternoon
9. Areas of concern
Several stations remain to be cleared for the survey.

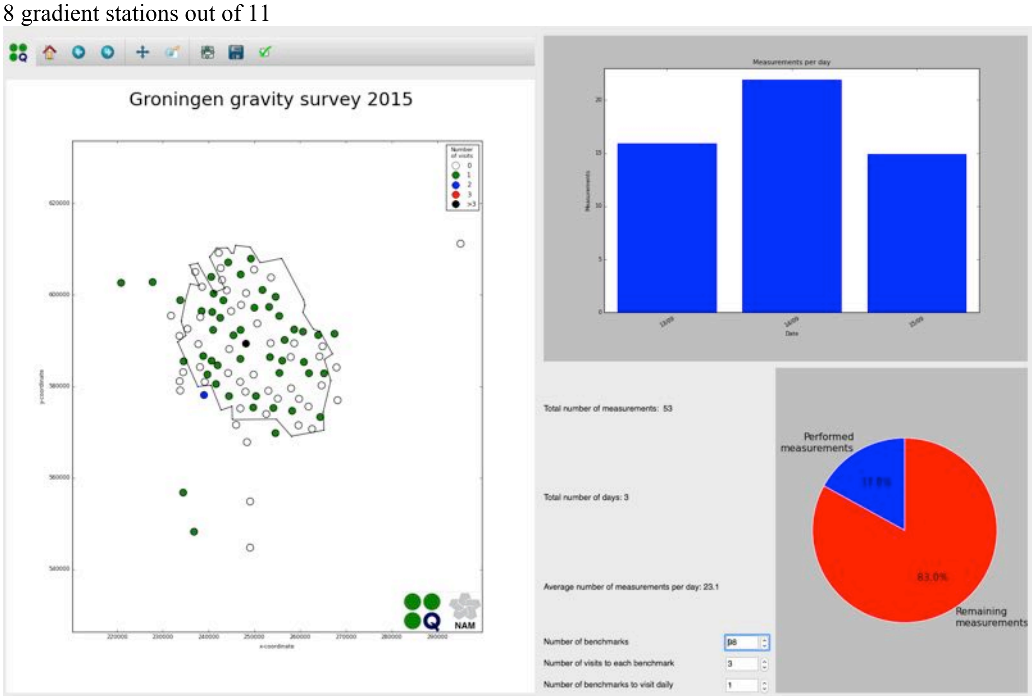
23.11 September 15th

1. Ongoing activity
Measurement at station 132 Groningen Groningerweg
2. HSE
Toolbox talks before each shift, and at each shift change in the field.
Billy Hatfield did the LSR + video + NAM pass in Assen.
VCA exam remaining for Rob Paesens and Ronald de Jong.
3. Activities last 24 hours (until 8:00)
24 measurements at stations 158, 4, 156, 164, 142, 304, 160, 131, 12, 135, 404, 125, 130, 204, 141, 150, 202, 154, 33, 149, 144, 6, 201, 208
All measurements have gone well.
Scouting revealed a coordinate update in our lists on 204, and a long distance from road (65m) for 128 (seismic station 28). Another choice of station is there preferable.
4. Planned activities next 24 hours
Measurements at 132, 404, 15, 17, 161, 22, 13, 9, 210, 121, 117, 203, 106, 110, 114, 404 and then remaining cleared stations in the southeast.
5. Overall progress
45 station measurements out of about 300; 15% completed
8 gradient stations out of 11
6. Accuracy of measurements
Time series look good. We will send updates tonight. Report in PDF-version will be made from tomorrow; with status maps. Today scouting of stations will take Ola's priority.
7. Long-term forecast
Continue surveying.
Absolute measurements in Overschild by TU Delft is scheduled for Wednesday-Thursday 16th-17th September.
8. Weather forecast next 24 hours
11-16 oC, rainy, windy
9. Areas of concern
About 16 stations remain to be cleared for the survey.

23.12 September 16th

1. Ongoing activity
Measurement at station 146 Noordbroek

2. HSE
Toolbox talks before each shift, and at each shift change in the field.
VCA exam remaining for Rob Paesens and Ronald de Jong.
3. Activities last 24 hours (until 8:00)
21 measurements at stations 132, 404, 15, 17, 161, 22, 13, 9, 133, 167, 114, 110, 106, 203, 19, 404, 30, 8, 507, 209, 146.
Gravity unit 12 failed on site 133. It was replaced with unit 11, and units 10, 11 and 13 have worked well since. Search of fault lasted 2 hours. Accompanying fault on iPad network contributed to the delay. TomTom settings and coordinates were improved to ease finding the benchmarks. Cause of the fault on unit 12 was identified during the evening, and a circuit board replaced. It is now stabilizing and ready for measurements again.
Scouting revealed that station 117 (seismic) is not possible to reach. The church in Westerwijtwerd is a possible replacement.
4. Planned activities next 24 hours
Measurements at 165, 155, 151, 205, 206, 3, 5, 211, 157, 153, 148, 137 and then additional stations that have been cleared during the day, together with some repeats.
Rigging and start of absolute measurement in Overschild.
5. Overall progress
66 station measurements out of about 300; 22% completed
8 gradient stations out of 11



6. Accuracy of measurements
QC plots will be sent later today.
7. Long-term forecast
Continue surveying.
8. Weather forecast next 24 hours
12-19 oC, showers, breeze
9. Areas of concern
About 16 stations remain to be cleared for the survey.

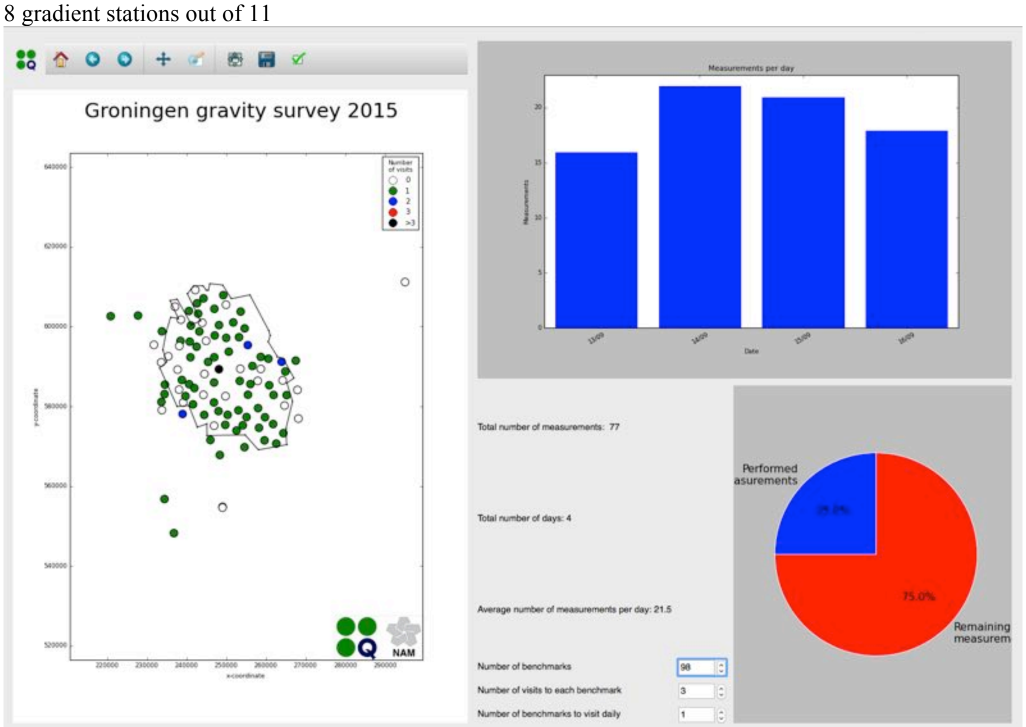
23.13 September 17th

1. Ongoing activity
Measurement at station 128 Woltersum church.
2. HSE
Toolbox talks before each shift, and at each shift change in the field.
VCA exam remaining for Rob Paesens and Ronald de Jong.

3. Activities last 24 hours (until 8:00)
19 measurements at stations 165, 151, 206, 205, 3, 5, 155, 211, 157, 137, 120, 518, 140, 303, 166, 168, 169, 132, 134.
Gravity units are working well without issues last 24 hours. IPad is connected to internet again, giving online positions.
Some waiting on access to a NAM plant and opening of a barrier.
A teleseismic earthquake of Magnitude 8 in Chile occurred 00:54 European time, and caused noise in several of the following records. These record will be assessed closer later this morning.
René Reudink arrived Overschild about 1:30, rigged up the FG-5 absolute instrument and started overnight recording. May be affected by the Chile earthquake.

4. Planned activities next 24 hours
Measurements at 128, 303, 401 (Aurich), 404 and further program dependent on today's scouting of stations released yesterday.
Currently 3 sites without access, 3 NAM sites that require marking and coordinates or photos before measurement, new Winsum site that needs coordinates or photos, 5 stations that will be scouted and defined by Quad today and one station (153) where contact number to the owner is needed for getting access.

5. Overall progress
85 station measurements out of about 300; 28% completed
8 gradient stations out of 11



Status plots at midnight.

6. Accuracy of measurements
Some QC plots up to yesterday morning are attached.
Drift variations of 12-24 h periods are seen.
11 repeat measurements have standard deviation of about 4 Gal with linear drift correction, 3 Gal with some finer drift correction.

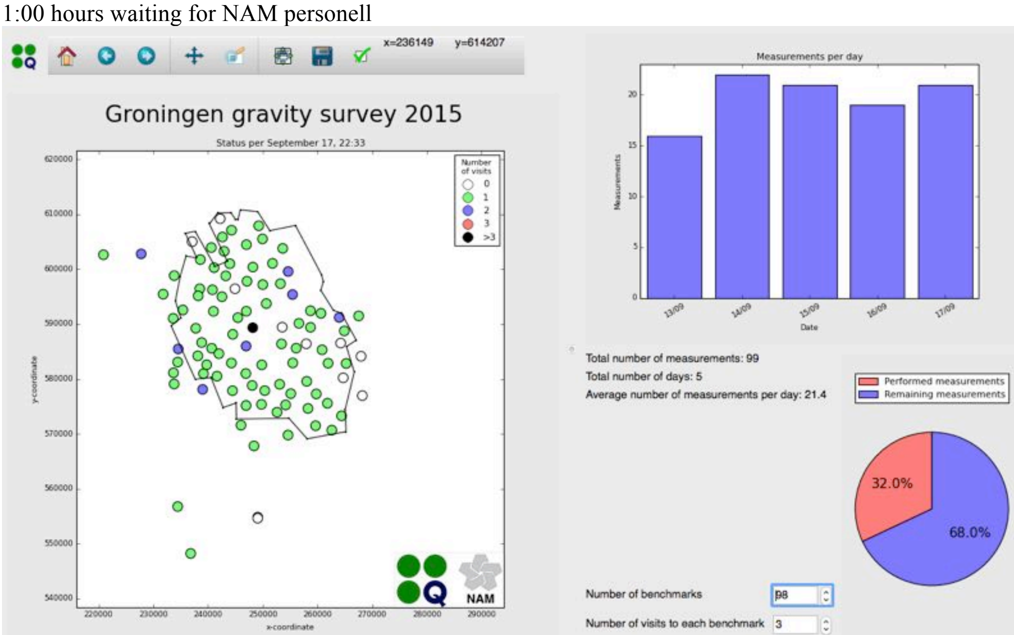
7. Long-term forecast
Continue surveying.

8. Weather forecast next 24 hours
15-18 oC, showers in the afternoon, breeze

9. Areas of concern
None.

23.14 September 18th

1. Ongoing activity
Measurement at station 504 Tusschenklap.
2. HSE
Toolbox talks before each shift, and at each shift change in the field.
VCA exam remaining for Rob Paesens and Ronald de Jong.
3. Activities last 24 hours (until 8:00)
21 measurements at stations 128, 306, 401, 404, 210, 108, 109, 302, 20, 14, 117, 121, 127, 139, 140, 34, 305, 143, 148, 2, 35
Opening of barriers at 210 and 108 worked well, without loss of time.
Gravity units are working well without issues last 24 hours. 40 minutes waiting on access to measurement at Aurich hospital, due to a misunderstanding with their technical leader.
René Reudink completed the absolute gravity measurement in Overschild in the morning, and then measured gravity gradients in the windmill. Although the earthquake disturbed the measurement for at least one hour, the uncertainty of the whole series seem to be below 2 Gal (preliminary assessment).
Ola scouted the remaining locations during the day.
Heavy rainfall in the afternoon will increase the water content in the ground, and may affect gravity for some time.
4. Planned activities next 24 hours
Measurements at 303, 404, 167, 516, 17, 13, 5, 156, 151 and further program dependent on accessibility of remaining not cleared station.
Currently 5 sites that are not cleared for measurements; NAM sites 10 Schildmeer, 21 Usqert and 207 Zeerijp that require marking and coordinates or photos, station 153 where a gate must be unlocked or the church in Beerta could be used, and station 301 that remains to be defined / accessibility cleared.
5. Overall progress
106 station measurements out of about 300; 35% completed
8 gradient stations out of 11
2:00 hours technical downtime
1:00 hours waiting for NAM personell



Status plots at midnight.
6. Accuracy of measurements
20 repeat measurements have standard deviation of about 6 Gal with linear drift correction, 4 Gal with some finer drift correction.
The earthquake yesterday caused noise in five consecutive records. They do not show deviating repeatabilities. The tidal gravimeters registered the earthquake well, and may be used for QC purposes in the post-processing.
A Google disk has been set up for sharing data in the project, and will be filled up today.

7. Long-term forecast

Continue surveying.
8. Weather forecast next 24 hours
11-19 oC, partly sunny, breeze
9. Areas of concern
None.

23.15 September 19th

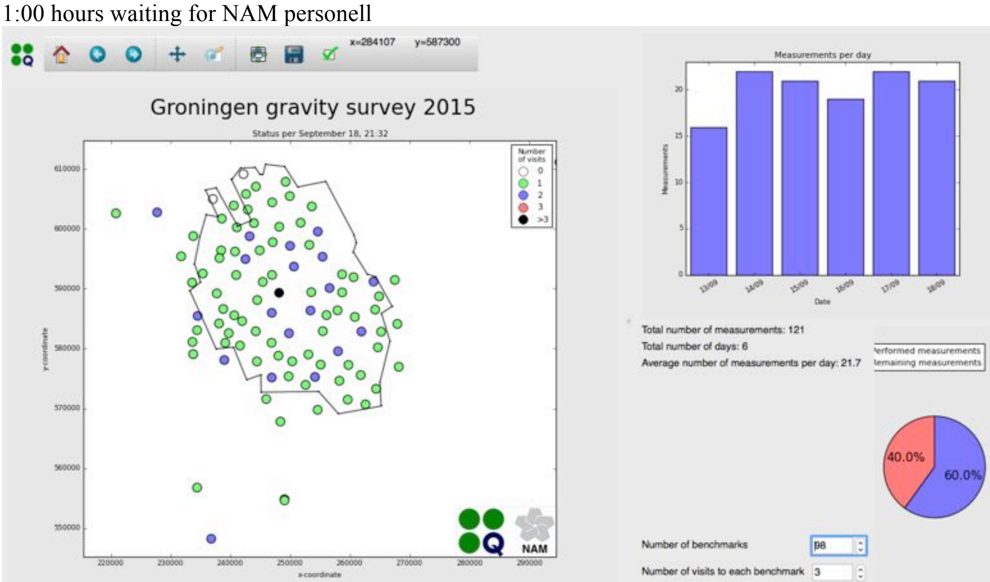
1. Ongoing activity
Measurement at station 105 Roodeschool.
2. HSE
A lengthy search for the Westerbork gravity bunker, in darkness, fog and with mobile connection turned off due to restrictions at the radio station put the crew at some risk. This should be avoided by daytime visits and more accurate coordinates in future visits.
Toolbox talks before each shift, and at each shift change in the field.
VCA exam remaining for Rob Paesens and Ronald de Jong.
3. Activities last 24 hours (until 8:00)
21 measurements at stations 4, 303, 404, 167, 516, 17, 13, 207, 5, 135, 10, 130, 142, 153, 402, 404, 8, 403, 521, 104, 19
A good day's work. Operations have gone well and gravity units are working well.
The gravimeters were protected from the sunshine during the day by the shield. Station 17, done at 1 pm local time, was in a hook facing the sun, and some extra temperature rise was inevitable.
At Westerbork in the late evening, fog and unintentional misguiding from the guard on watch caused a lengthy search for the bunker. Now all the shift leaders have been to the bunker and know the area, but for future surveys, a coordinate update (the current was 50 m from the bunker) and measurements during daytime will be better.
Scouting at Winschoten railway station and intelligence from locals revealed that the interior of the building has been completely rebuilt since 1999. It may be possible to reconstruct the location, but it will require significant work and the result is uncertain. I propose to give up the station for this survey. The new station 157 is 1 km away from the railway station.

1999

2015

Pictures from inside the Winshoten railway station. This shall according to locals be the same room, looking in the same direction.
4. Planned activities next 24 hours
Measurements at stations 110, 115, 304, 143, 211, 156, 155, 202, 149, 7, 139, 201, 404 and further stations which have previously been visited once, and that are accessible in the weekend.
Site 301 remains to be defined / accessibility cleared. An alternative location 2 km further west has free access, but seems less optimal with respect to reservoir geometry and water inflow signal. Currently the gas transport facility site is investigated. 301 is the only site that has not been measured yet.
5. Overall progress
127 station measurements out of about 310; 41% completed
8 gradient stations out of 11

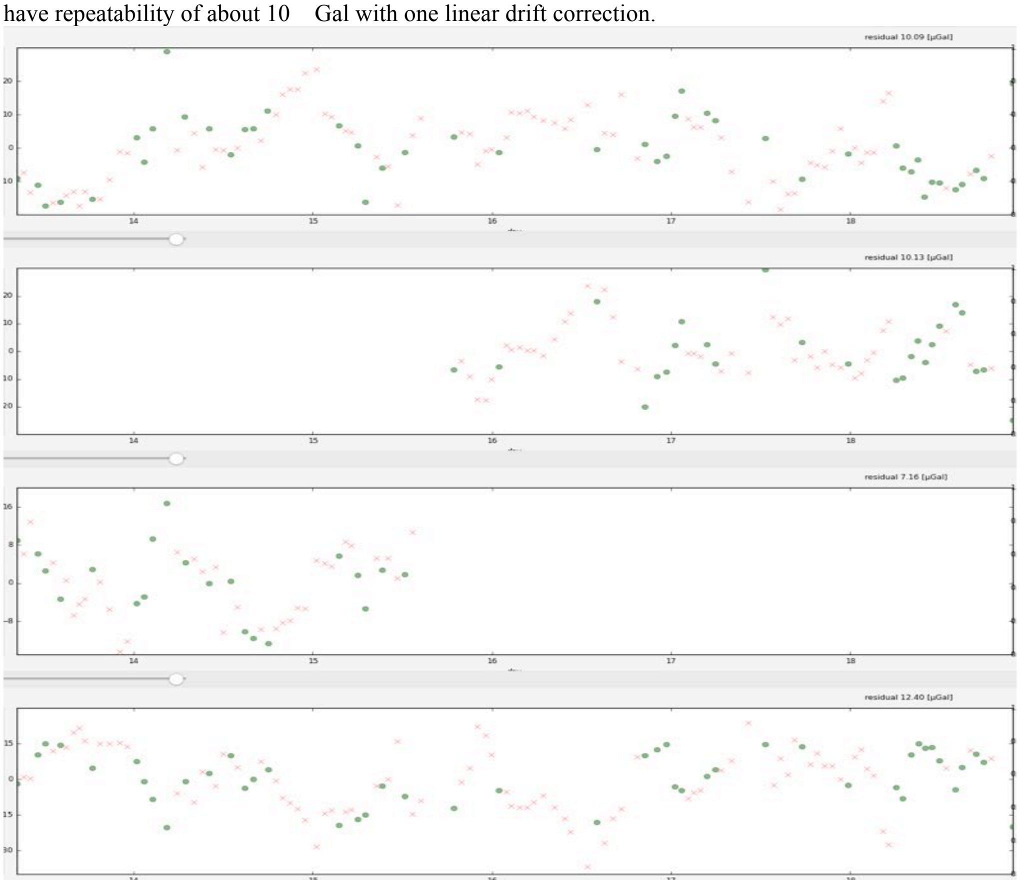
2:00 hours technical downtime
1:00 hours waiting for NAM personell



Status plots at midnight.

6. Accuracy of measurements

45 repeat measurements have standard deviation of about 6 Gal with one linear drift correction only. Individual sensors have repeatability of about 10 Gal with one linear drift correction.

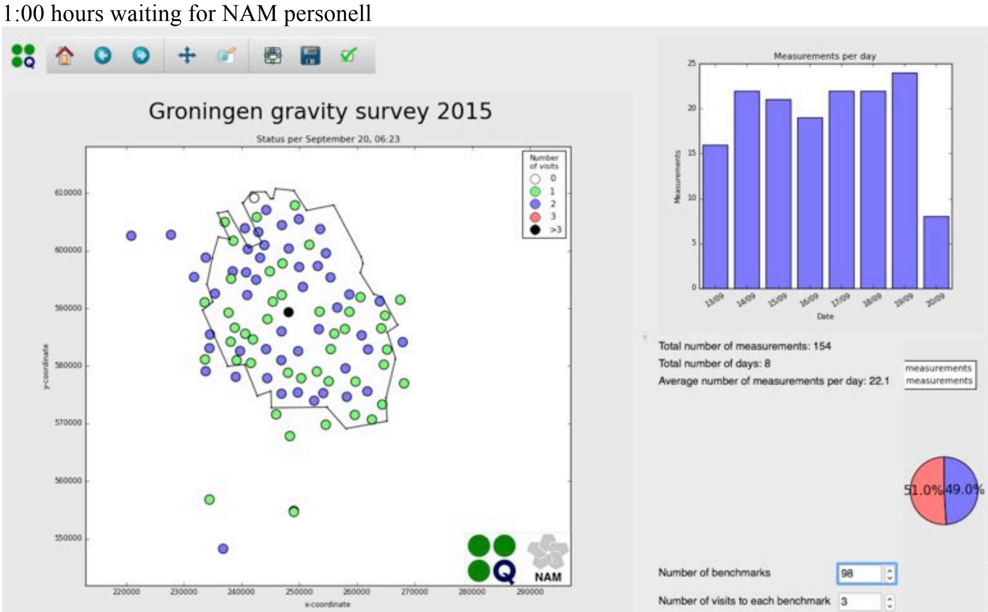


Station repeatability for all units (10, 11, 12 and 13 from top to bottom), with one linear drift correction.

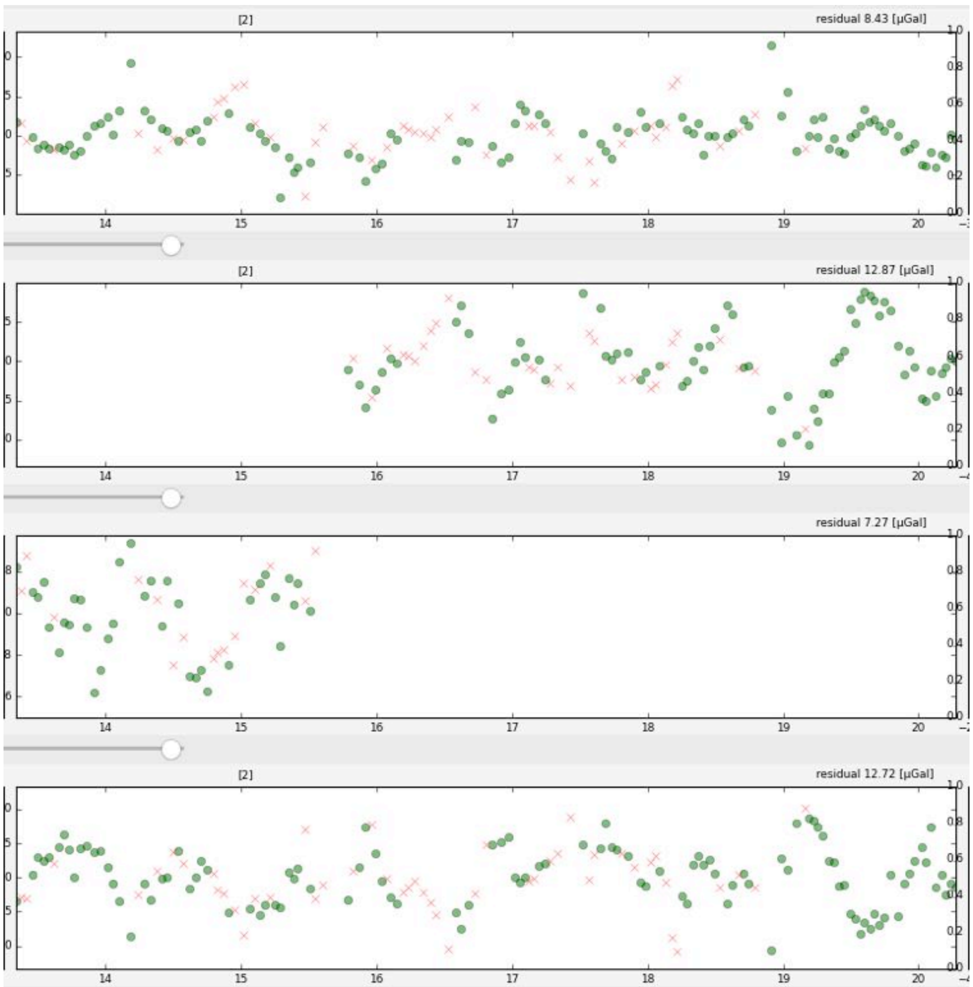
7. Long-term forecast
With the current speed of operation, the main survey will be completed by the end of Sunday 27th September.
3 remaining gradient measurements to be done thereafter.
8. Weather forecast next 24 hours
13-17°C, light showers, breeze
9. Areas of concern
None.

23.16 September 20th

1. Ongoing activity
Measurement at station 208 Eemskanaal.
2. HSE
Toolbox talks before each shift, and at each shift change in the field.
VCA exam remaining for Rob Paesens and Ronald de Jong.
3. Activities last 24 hours (until 8:00)
26 measurements at stations 105, 110, 115, 125, 304, 143, 211, 156, 155, 202, 149, 507, 139, 201, 404, 166, 121, 113, 161, 101, 302, 106, 109, 112, 514, 15.
A good day's work. Operations have gone well and gravity units are working well.
4. Planned activities next 24 hours
Measurements at stations 122, 208, 141, 34, 164, 148, 157, 154, 209, 144, 169, 404, 114 and further stations which have previously been visited once, and that are accessible in the weekend.
Site 301 remains to be defined / accessibility cleared.
5. Overall progress
153 station measurements out of about 310; 49% completed
8 gradient stations out of 11
2:00 hours technical downtime
1:00 hours waiting for NAM personell



Status plots at 9 am local time.
6. Accuracy of measurements
105 repeat measurements have standard deviation of about 6 Gal with one linear drift correction only. Individual sensors have repeatability of about 10 Gal with one linear drift correction.



Station repeatability for all units (10, 11, 12 and 13 from top to bottom), with one linear drift correction.

7. Long-term forecast

With the current speed of operation, the main survey will be completed late Sunday 27th September.
3 remaining gradient measurements to be done thereafter.

8. Weather forecast next 24 hours

13-17°C, partly cloudy, light showers in the afternoon

9. Areas of concern

None.

23.17 September 21st

1. Ongoing activity

Measurement at station 153 Beerta church.

2. HSE

Toolbox talks before each shift, and at each shift change in the field.
VCA exam remaining for Rob Paesens and Ronald de Jong.

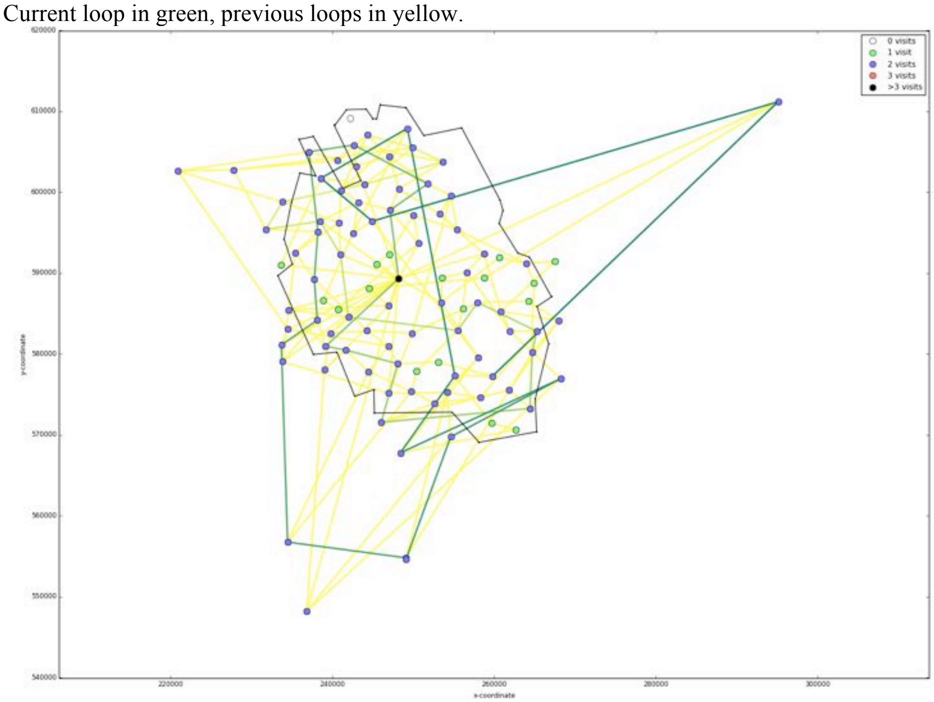
3. Activities last 24 hours (until 8:00)

24 measurements at stations 122, 208, 141, 34, 164, 148, 157, 154, 209, 144, 169, 404, 114, 162, 203, 521, 117, 127, 168, 30, 33, 2, 35, 158.
A good day’s work. Operations have gone well and gravity units are working well.

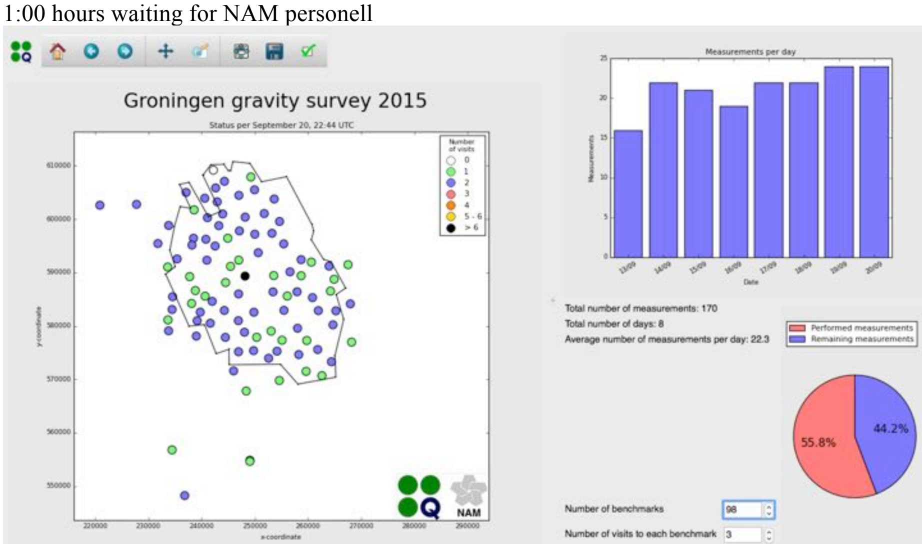
4. Planned activities next 24 hours

Measurements at stations 153, 3, 151, 153, 22, 108, 207, 401 and further stations which have previously been visited once.
Some stations will get a third visit before we can access the remaining NAM and barrier stations for second visit tomorrow.

Site 301 remains to be defined / accessibility cleared.
Current loop in green, previous loops in yellow.

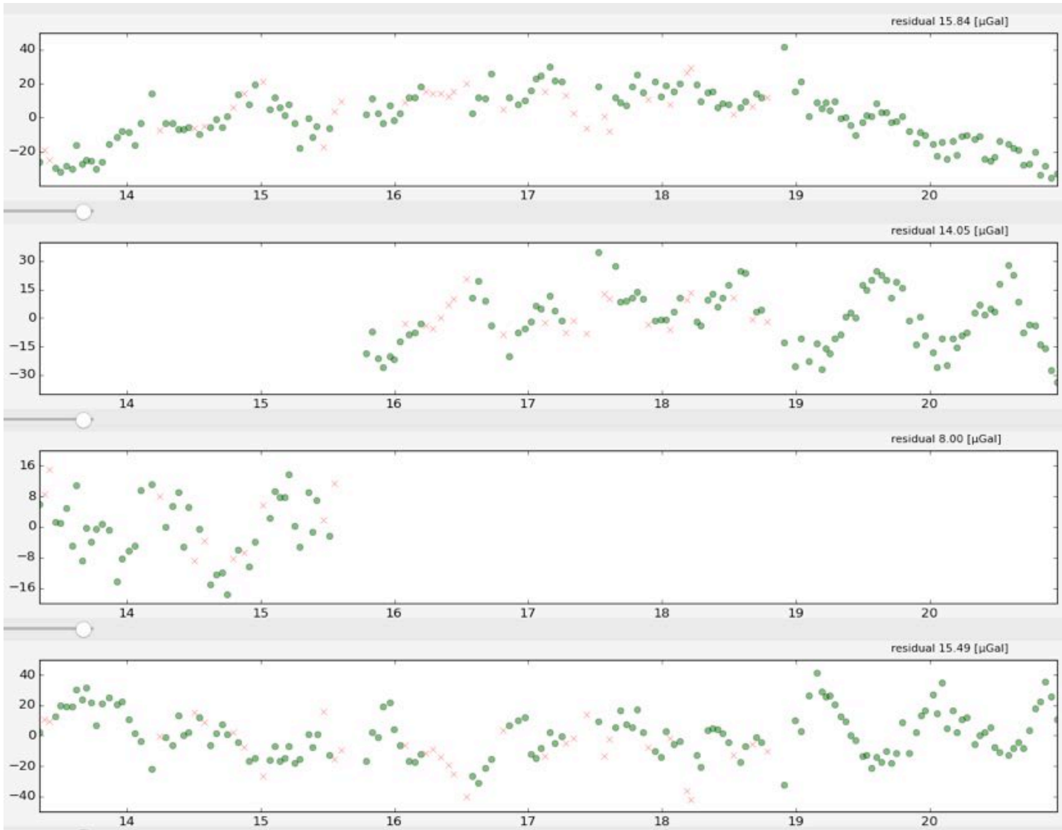


5. Overall progress
177 station measurements out of about 310; 57% completed
8 gradient stations out of 11
2:00 hours technical downtime
1:00 hours waiting for NAM personell



Status plots at 1 am local time.

6. Accuracy of measurements
Repeatability plot with only one linear drift correction is shown. Other QC plots have been uploaded to the common Google-disk. A more sophisticated drift solution will be placed on the Google disk shortly.



Station repeatability for all units (10, 11, 12 and 13 from top to bottom), with one linear drift correction.

7. Long-term forecast

With the current speed of operation, the main survey will be completed Sunday 27th September.

3 remaining gradient measurements to be done thereafter.

8. Weather forecast next 24 hours

13-17^{o}C, cloudy

9. Areas of concern

None.

23.18 September 22nd

1. Ongoing activity

Measurement at station 511 Ten Post.

2. HSE

Toolbox talks before each shift, and at each shift change in the field.

VCA exam remaining for Rob Paesens and Ronald de Jong.

3. Activities last 24 hours (until 8:00)

20 measurements at stations 3, 151, 22, 301, 108, 207, 127, 133, 510, 306, 160, 305, 153, 165, 150, 303, 128, 204, 137, 518.

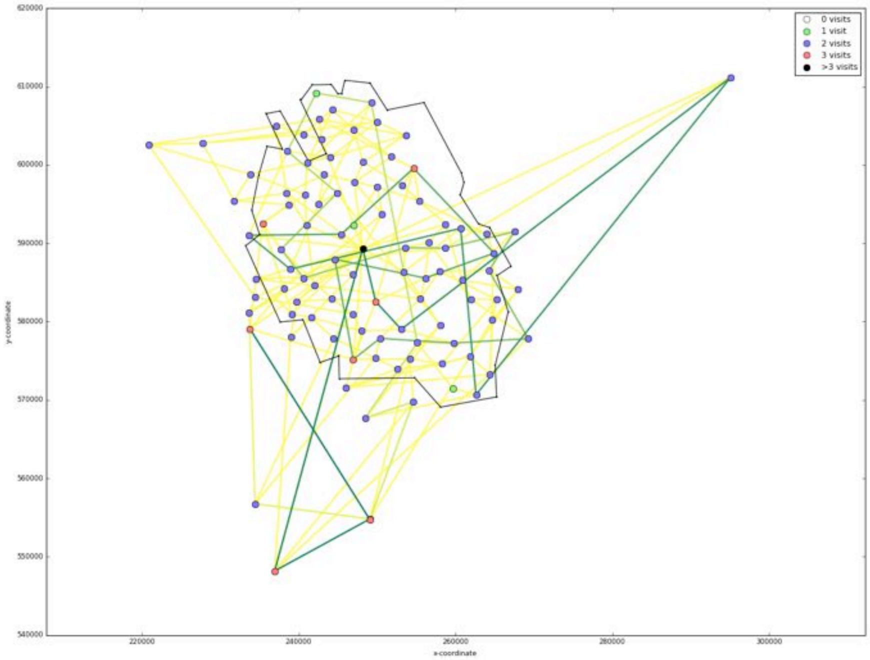
Unit 11 gave intermittent bad signals at 8 o'clock yesterday. A re-start did not help, and it was decided to swap the unit with the spare unit 12 again. This was done at Ten Boer, and 9:15 the crew was on its way again. Unit 11 is under observation; currently it does not show faulty behavior. Further diagnostics is run.

Site 301 got its first visit, with access through the area of Noordgastransport. The site was at the same time marked and positions read by Eric Pasma, the NAM surveyor,

4. Planned activities next 24 hours

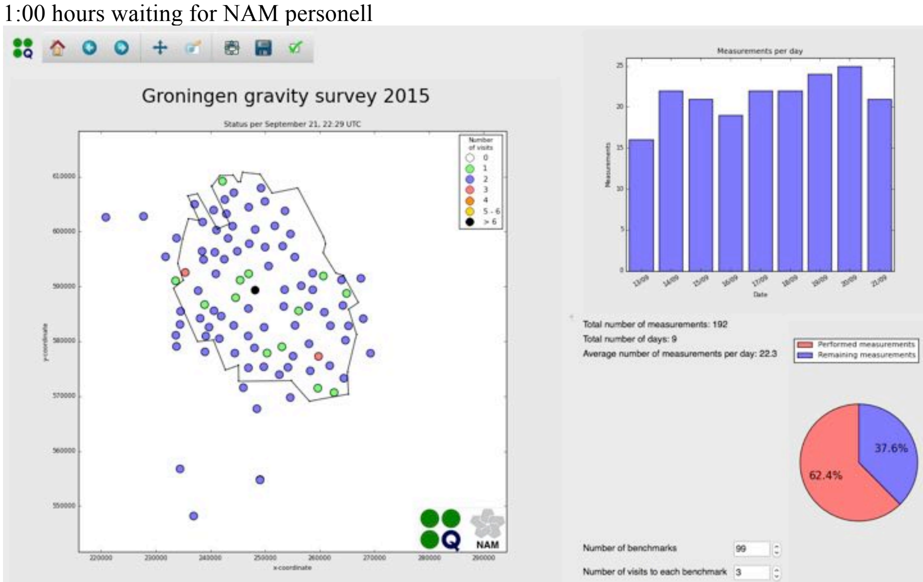
Measurements at stations 511, 210, 9, 512, 205, 401 (Aurich), 146, 140, 404, 402 (Westerbork), 2, 35, 166 and further. The first four stations will have barriers or be inside NAM plants, and Koert Schoon from NAM will accompany the crew.

Current loop in green, previous loops in yellow.



5. Overall progress

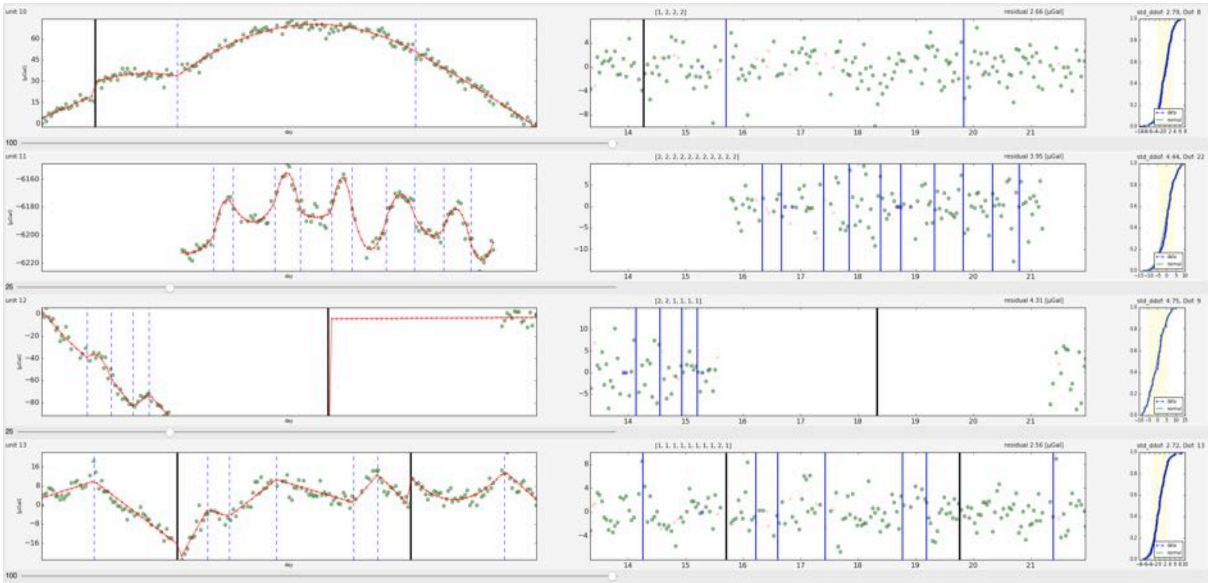
197 station measurements out of about 310; 64% completed
8 gradient stations out of 11
3:15 hours technical downtime
1:00 hours waiting for NAM personell



Status plots at 1 am local time.

6. Accuracy of measurements

Repeatability plot for each unit, after a joint dirft inversion, is shown:



Standard deviations of each unit are (in Gal): U10: 2.7, U11, 4.0, U12: 4.3, U13: 2.6.
Unit 11 has an about 20 Gal diurnal variation.
Adjusting the scale factors after the calibration Westerbork – Monschau reduced the scatter significantly.
Measurement repeatability (standard deviation) is <2.5 Gal.

7. Long-term forecast

With the current speed of operation, the main survey will be completed Sunday 27th September.
3 remaining gradient measurements to be done thereafter.

8. Weather forecast next 24 hours

13-16°C, cloudy, showers

9. Areas of concern

None.

23.19 September 23rd

1. Ongoing activity

Measurement at station 301 Norordpolderzijl.

2. HSE

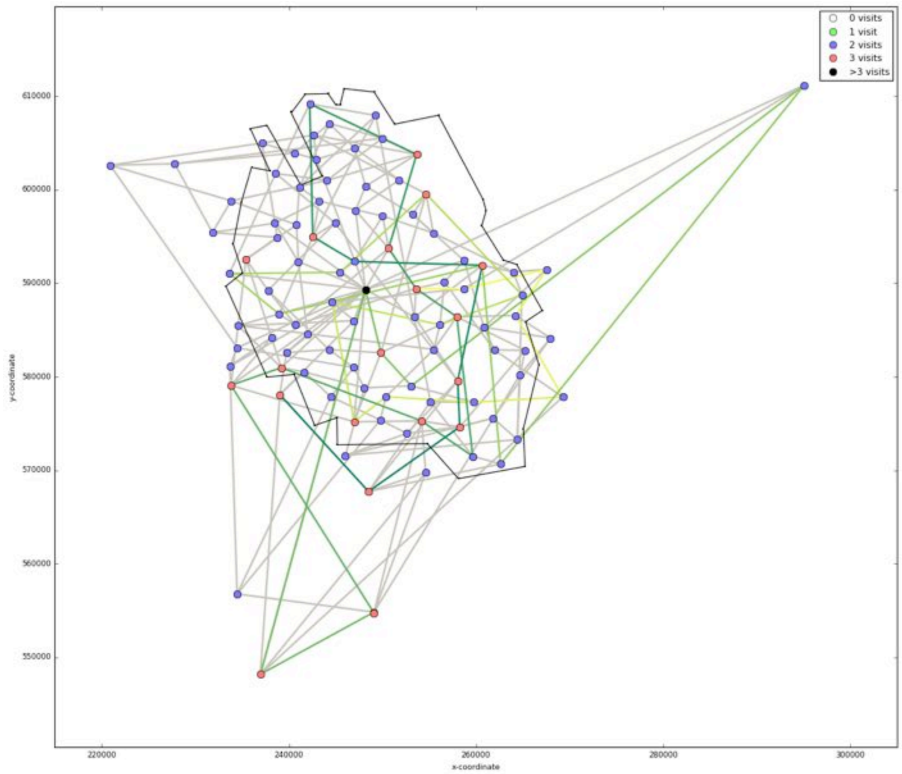
There were indications of fog early in the night, and the 1 am crew had attention on driving slowly if fog should cause poor visibility. However, the night in the North has passed without fog problems.
Toolbox talks before each shift, and at each shift change in the field.
VCA exam remaining for Rob Paesens and Ronald de Jong.

3. Activities last 24 hours (until 8:00)

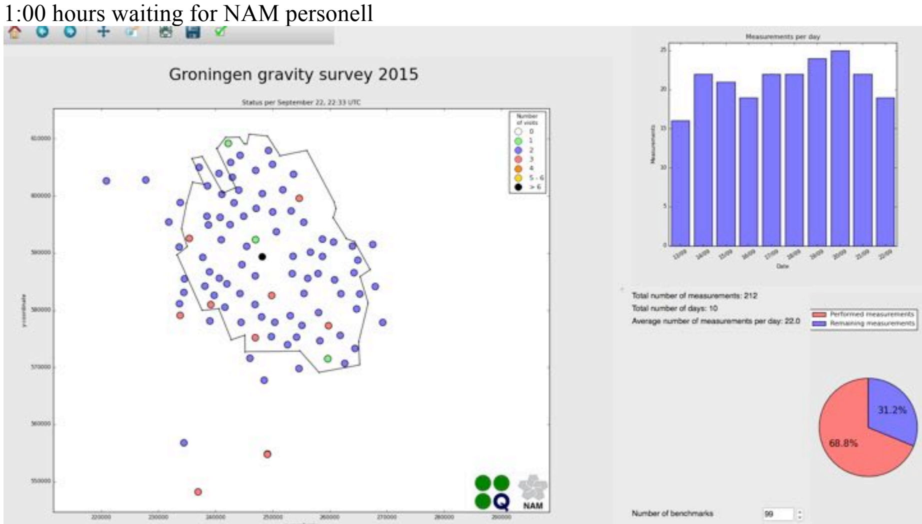
20 measurements at stations 511, 210, 9, 512, 205, 401, 146, 140, 404, 402, 2, 35, 166, 169, 504, 206, 34, 510, 167, 106.
Unit 12 is working fine.
The spare unit 11 is still under observation. All connectors have been gone over.
Measurements at Aurich and Westerbork went fine.

4. Planned activities next 24 hours

Measurements at stations 301, 13, 123, 12, 5, 156, 3, 506 and further. Four stations will be inside NAM plants, and Wilfred Danser from NAM will accompany the crew.
Current loop in green darker colors for planned and most recent visits. Previous loops in grey.

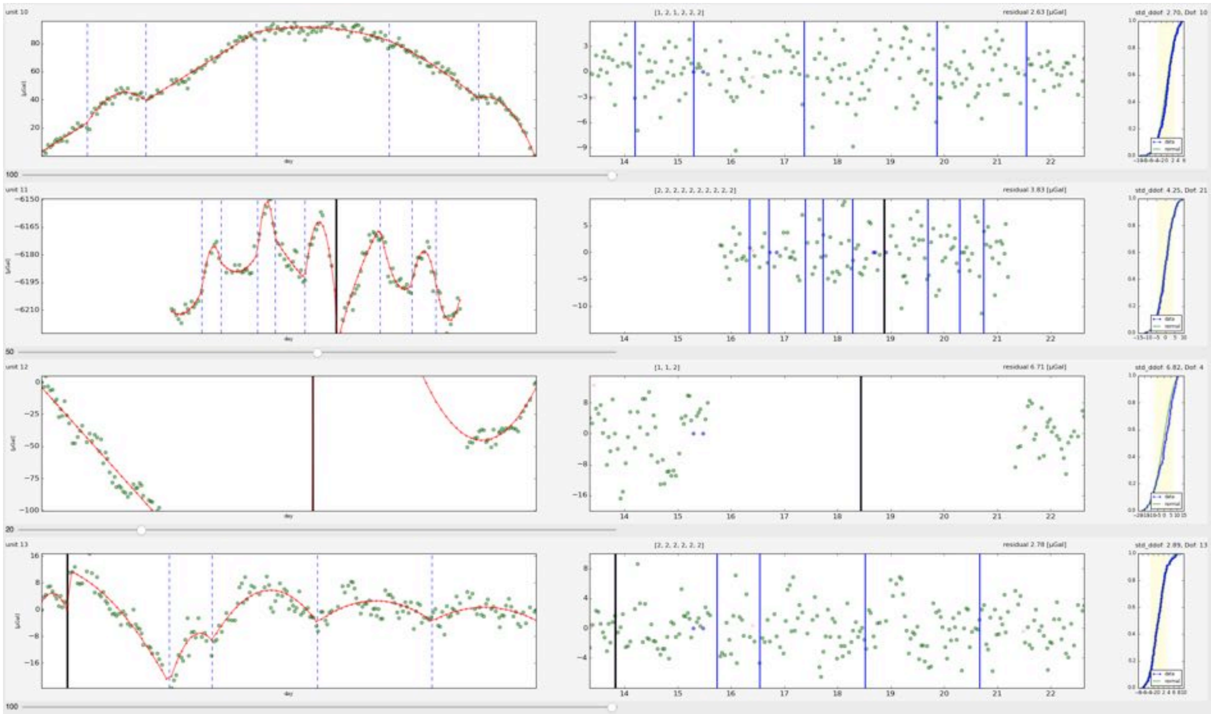


5. Overall progress
217 station measurements out of about 310; 70% completed
8 gradient stations out of 11
3:15 hours technical downtime
1:00 hours waiting for NAM personell

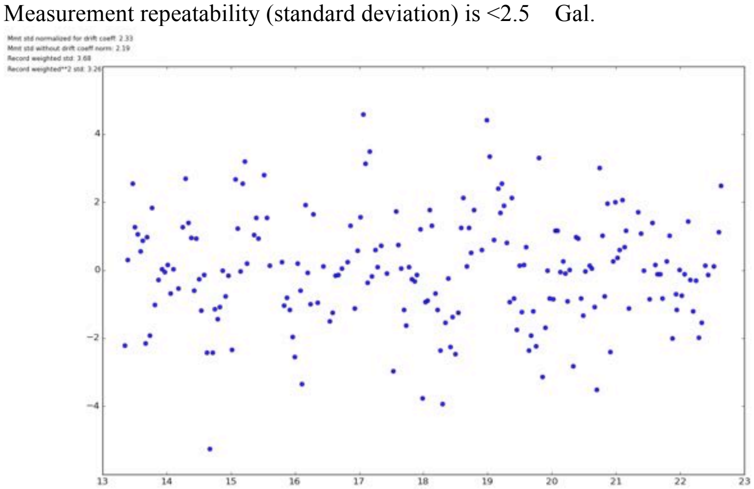


Status plots at 1 am local time.

6. Accuracy of measurements
Repeatability plot for each unit, after a joint drift inversion, is shown:



Standard deviations of each unit are (in Gal): U10: 2.7, U11, 3.8, U12: 6.7, U13: 2.8.
Unit 11 has an about 20 Gal diurnal variation.
Measurement repeatability (standard deviation) is <2.5 Gal.



7. Long-term forecast
With the current speed of operation, the main survey will be completed Sunday 27th September.
3 remaining gradient measurements to be done thereafter.
8. Weather forecast next 24 hours
11-18^{o}C, cloudy, rain in the afternoon
9. Areas of concern
None.

23.20 September 24th

1. Ongoing activity
Measurement at station 207 Zeerijp.
2. HSE

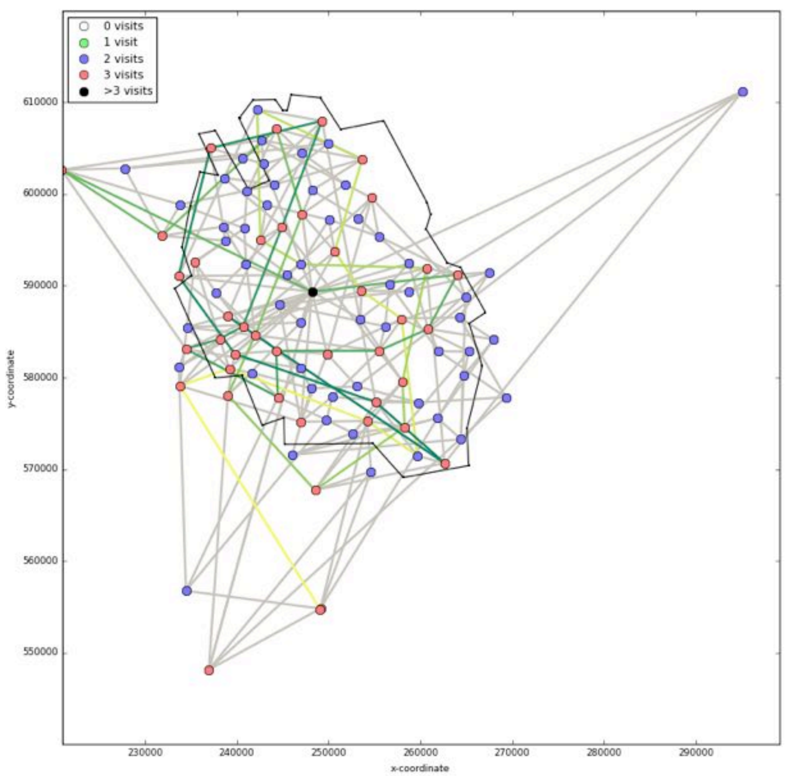
Toolbox talks before each shift, and at each shift change in the field.
VCA exam remaining for Rob Paesens and Ronald de Jong.

3. Activities last 24 hours (until 8:00)

22 measurements at stations 301, 13, 123, 512, 5, 156, 3, 506, 208, 114, 101, 514, 403, 404, 131, 304, 141, 139, 149, 8, 168, 133.
A good days work.
Entrance to 301 was this time via Watershap Noordpolderzijlvest's gate near the dike, 6.5 km east of the station. This caused some confusion, clarified with the help of Wim van der Veen's presence.
Contact with a local person at Gasselte the previous night was friendly, in spite of the fact that he had moved to get away from the earthquake area and now became worried why we were measuring at Gasselte. The crew explained it was a reference site.

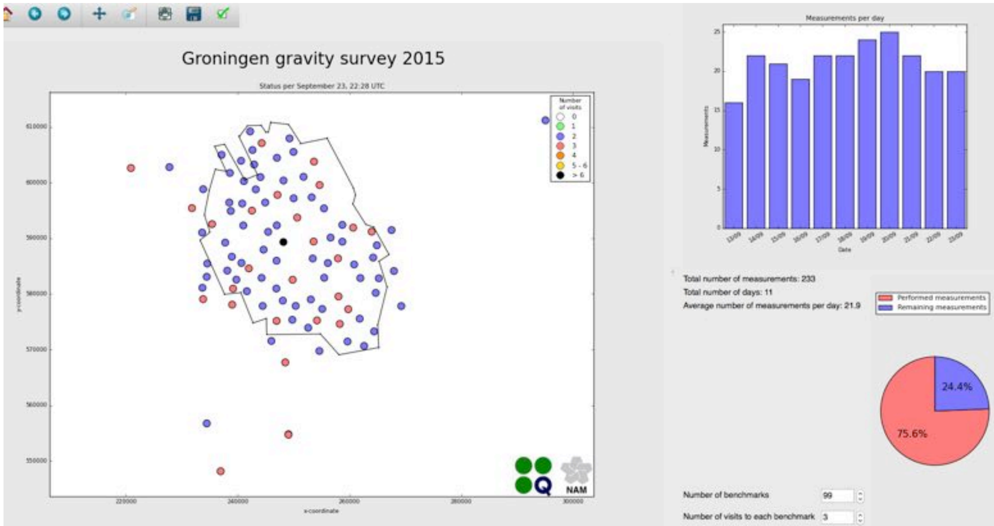
4. Planned activities next 24 hours

Measurements at stations 22, 521, 210, 201, 151, 205, 9 and further. Stations 9 and 22 will be inside NAM plants and stations 210, 151 and 205 will have barriers. Koert Schoon from NAM will accompany the crew for the day.
Current loop in green darker colors for planned and most recent visits. Previous loops in grey.



5. Overall progress

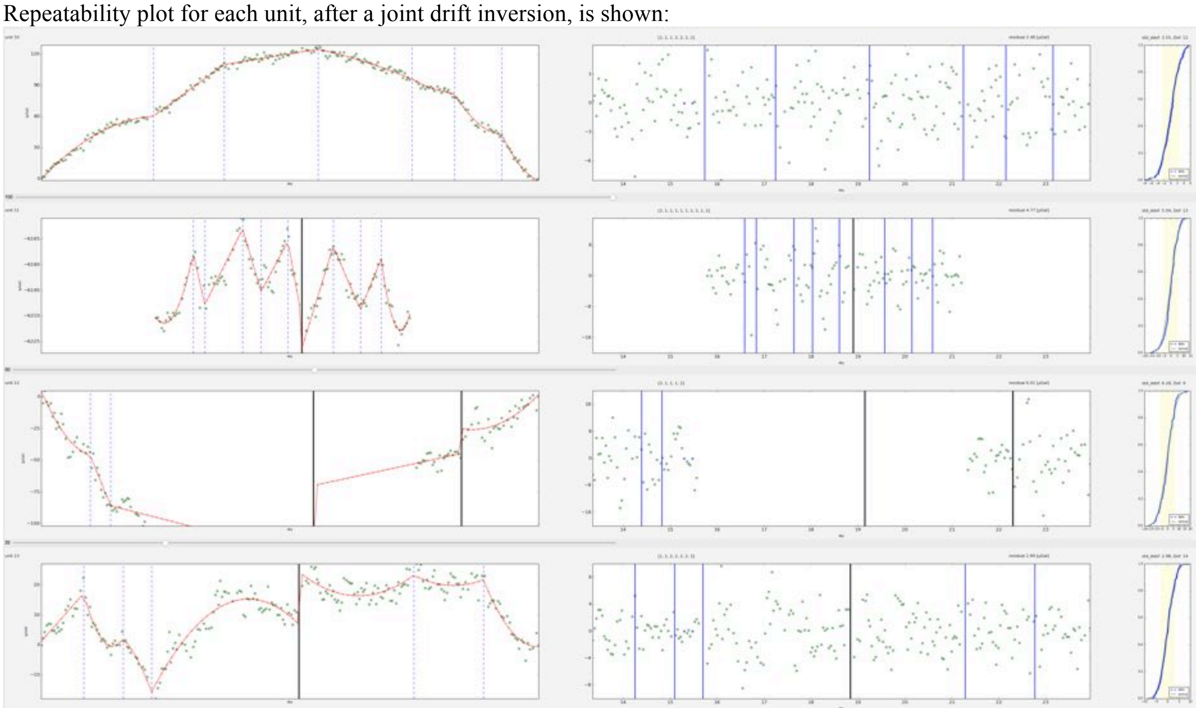
239 station measurements out of about 310; 77% completed
8 gradient stations out of 11
3:15 hours technical downtime
1:00 hours waiting for NAM personell



Status plots at 1 am local time.

6. Accuracy of measurements

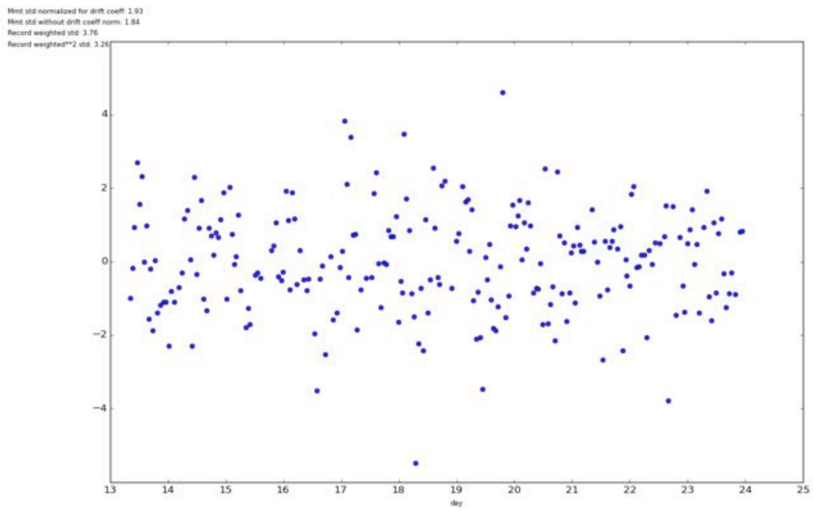
Repeatability plot for each unit, after a joint drift inversion, is shown:



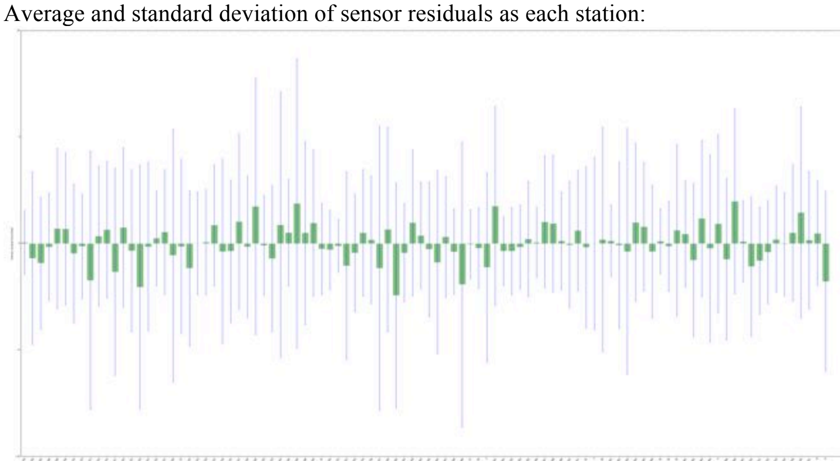
Standard deviations of each unit are (in μGal): U10: 2.5, U11, 4.8, U12: 6.0, U13: 2.9.

Unit 11 has an about 20 μGal diurnal variation.

Measurement repeatability (standard deviation) is <2.5 μGal.



Average and standard deviation of sensor residuals as each station:



The values for this plot is sent to Marcin in a separate mail.

7. Long-term forecast

With the current speed of operation, the main survey will be completed Sunday 27th September.

3 remaining gradient measurements to be done thereafter.

8. Weather forecast next 24 hours

12-15oC, partly cloudy, showers in the afternoon

9. Areas of concern

None.

23.21 September 25th

1. Ongoing activity

Measurement at station 22 Uithuizermeeden church.

2. HSE

VCA exams for the taxi drivers cannot be completed in time. Solution can be to carry on as is for the remaining two days, or to replace them with the extra Quad driver (and data processor).

3. Activities last 24 hours (until 8:00)

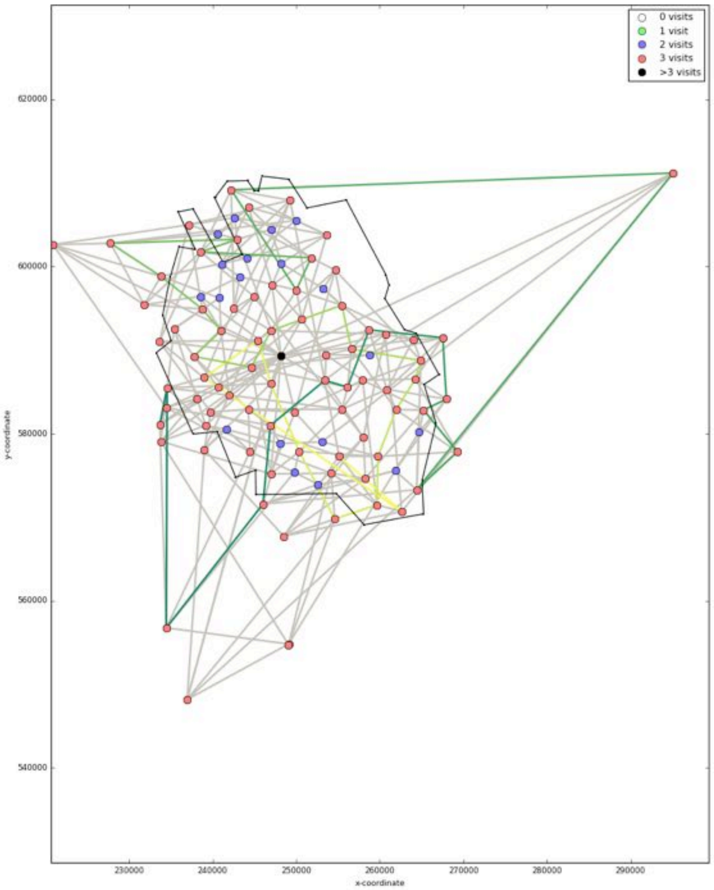
25 measurements at stations 207, 22, 521, 210, 201, 151, 205, 9, 511, 134, 150, 158, 206, 165, 142, 305, 137, 130, 120, 123, 128, 122, 117, 112, 520.

A good days work.

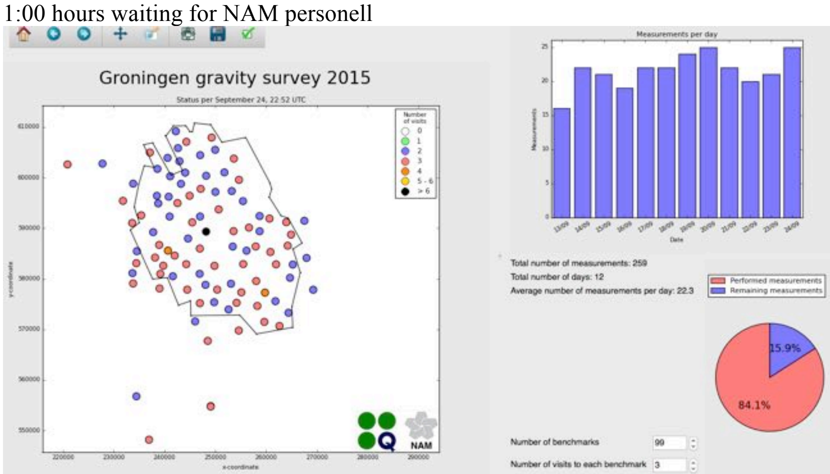
4. Planned activities next 24 hours

Measurements at stations 108, 162, 516, 301, 401(Aurich), 157, 153, 164, 143, 160, 125, 204, 135, 507, 154, 33, 132, 30.

Current loop in green darker colors for planned and most recent visits. Previous loops in grey.



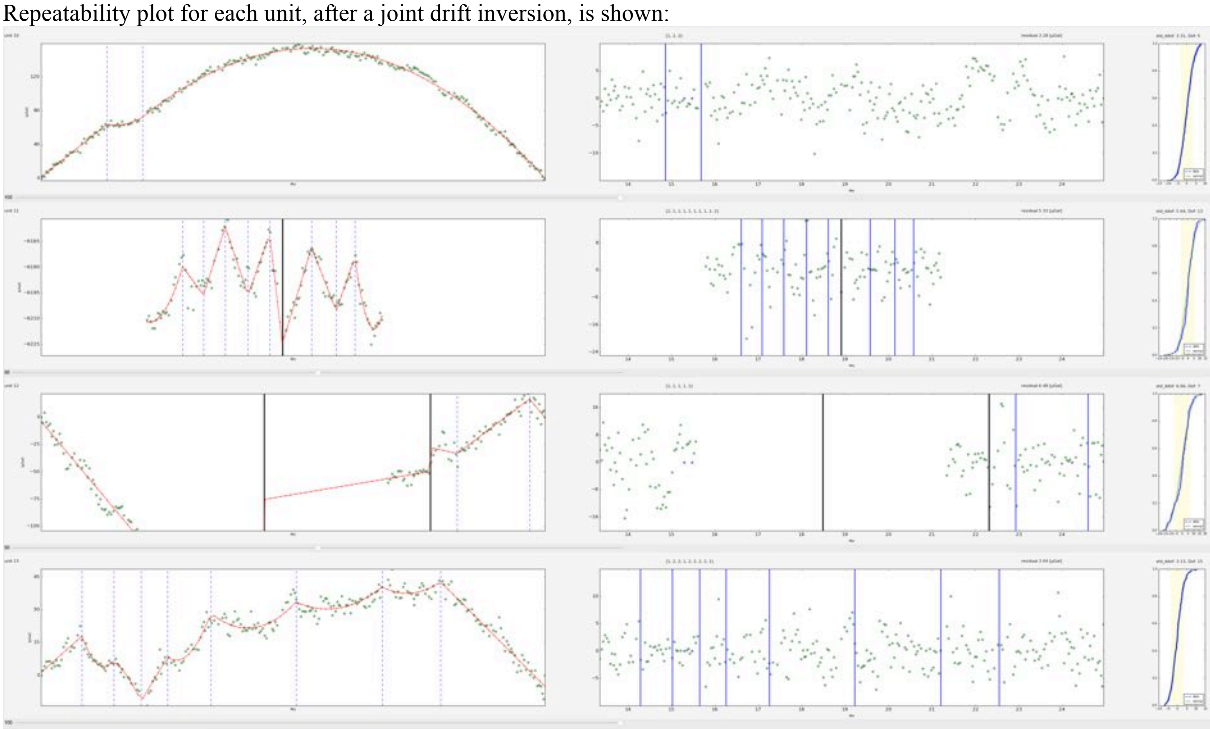
5. Overall progress
267 station measurements out of about 310; 86% completed
8 gradient stations out of 11
3:15 hours technical downtime
1:00 hours waiting for NAM personell



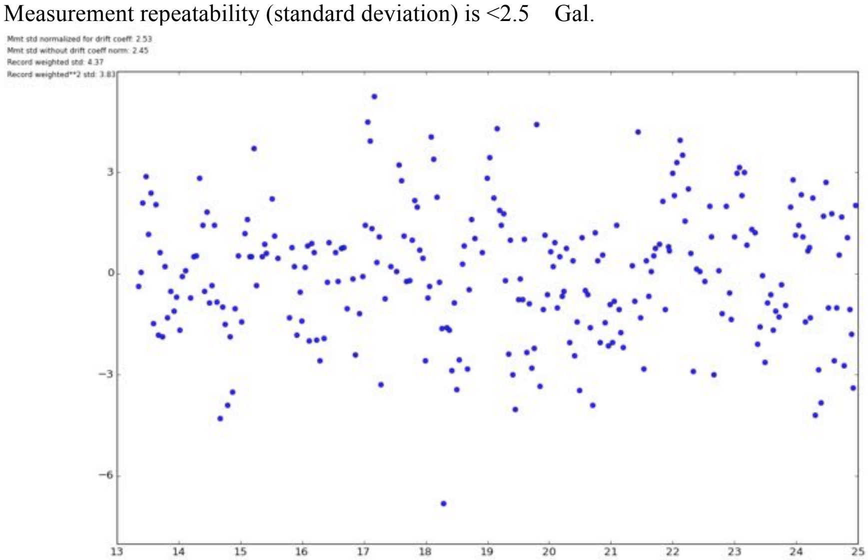
Status plots at 1 am local time.

6. Accuracy of measurements

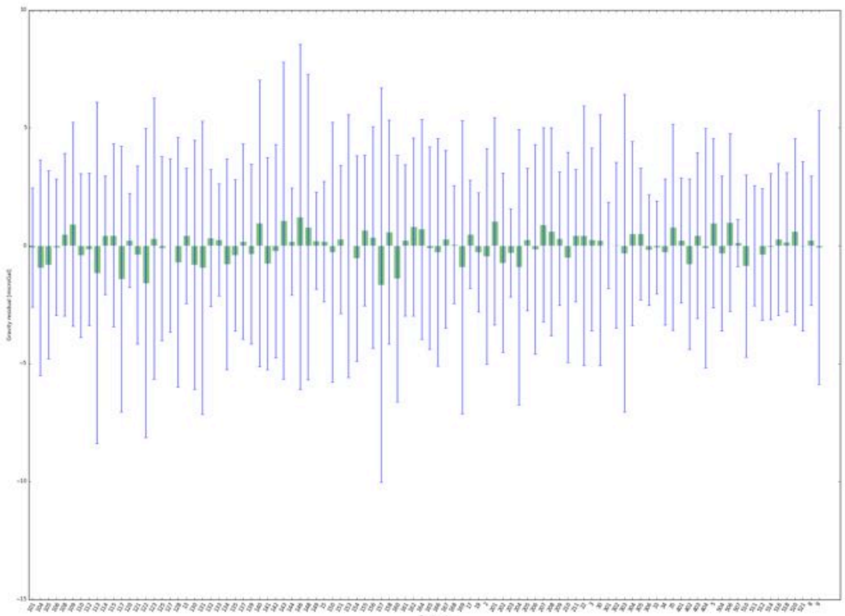
Repeatability plot for each unit, after a joint drift inversion, is shown:



Standard deviations of each unit are (in Gal): U10: 3.3, U11, 5.3, U12: 6.5, U13: 3.0.
Unit 11 has an about 20 Gal diurnal variation.
Measurement repeatability (standard deviation) is <2.5 Gal.



Average and standard deviation of sensor residuals as each station:



The values for this plot is put on the Google drive.

7. Long-term forecast

With the current speed of operation, the main survey will be completed Sunday 27th September.
3 remaining gradient measurements to be done thereafter.

8. Weather forecast next 24 hours

12-17^{o}C, sunny in the first part of the day, then cloudy

9. Areas of concern

None.

23.22 September 26th

1. Ongoing activity

Measurement at station 209 Froombosch.

2. HSE

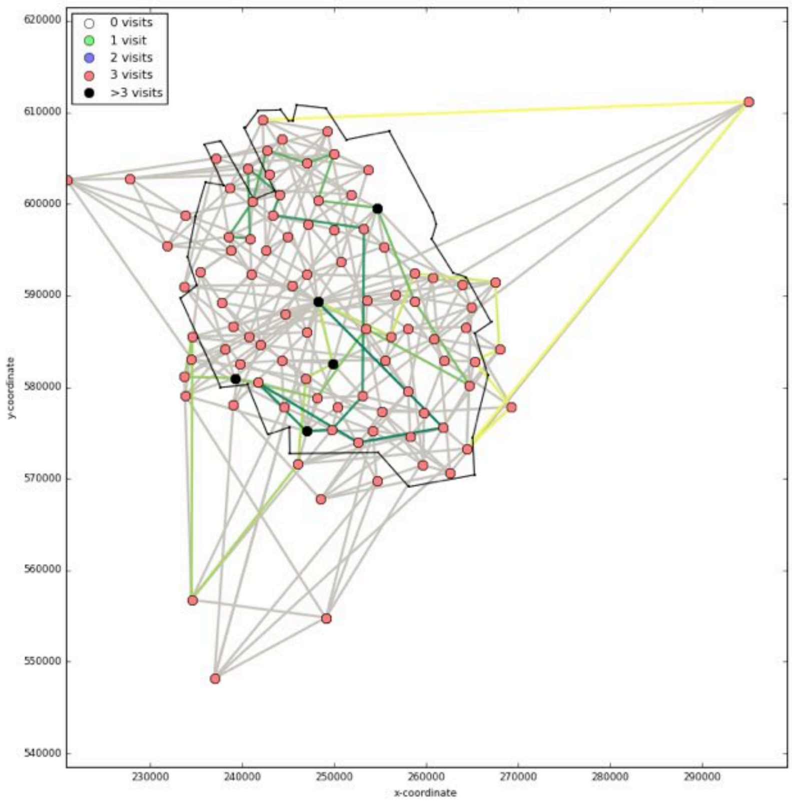
None

3. Activities last 24 hours (until 8:00)

22 measurements at stations 19, 108, 162, 516, 301, 401, 157, 153, 164, 143, 160, 125, 204, 404, 140, 507, 154, 33, 132, 30, 169, 209.
A good days work.

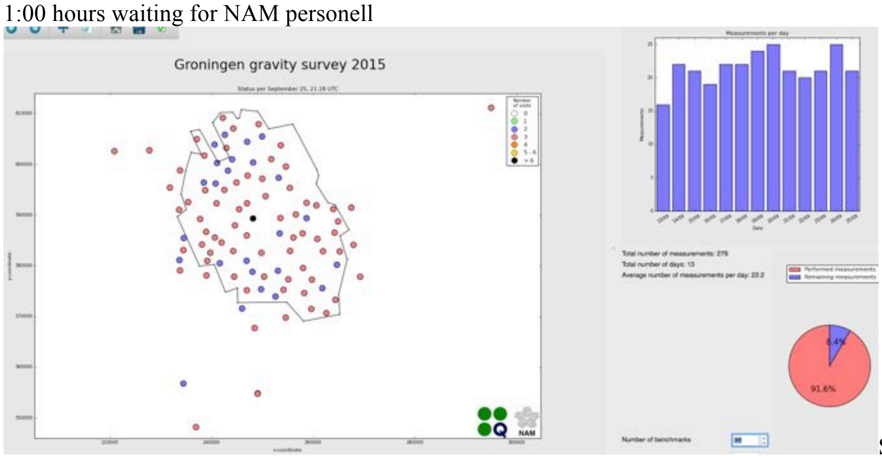
4. Planned activities next 24 hours

Measurements at stations 135, 148, 306, 518, 110, 302, 105, 203, 161, 15, 113, 104, 109, 17, 115, 146, 202, 303, 144, 155, 211, 404.
Ola travel by train to Zwolle and Maastricht, to scout at the railway station sites measured in 1984.
Recent and next measurements in green and yellow colors; darker for later in the survey. Previous loops in grey.



5. Overall progress

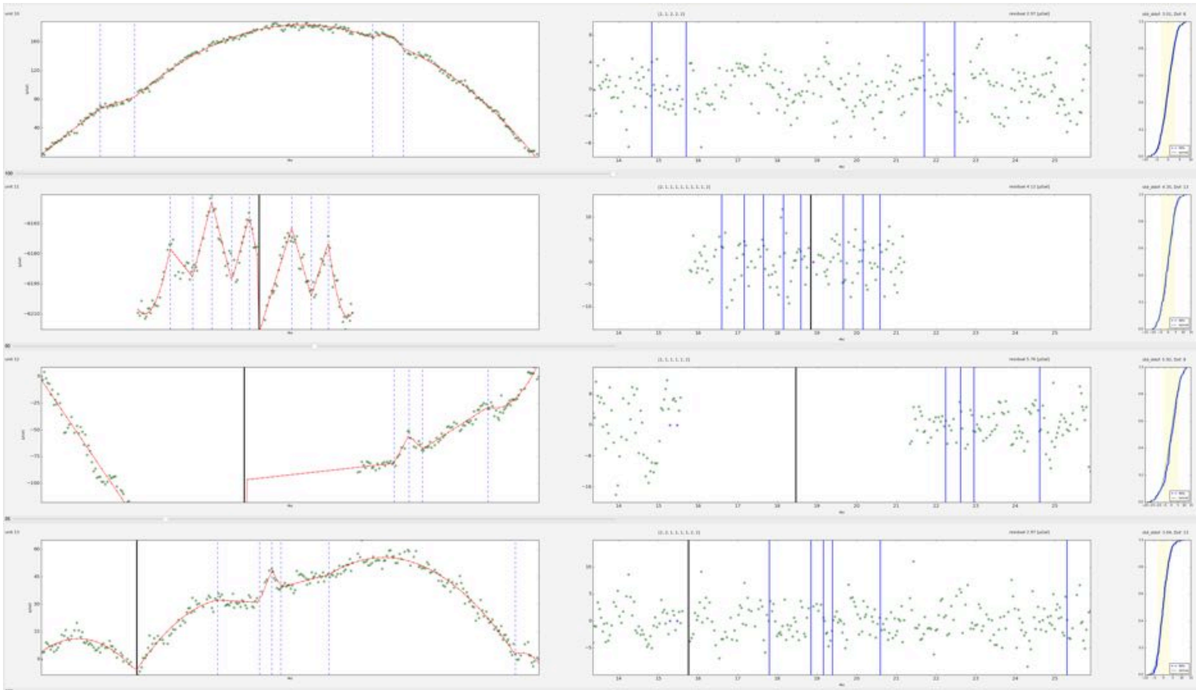
287 station measurements out of 309; 93% completed
8 gradient stations out of 11
3:15 hours technical downtime
1:00 hours waiting for NAM personell



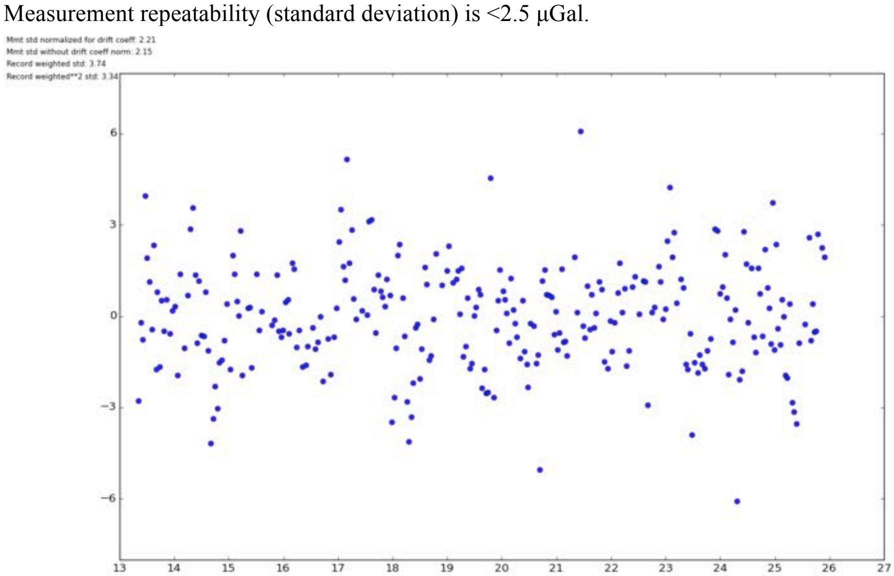
Status plots at 1 am local time.

6. Accuracy of measurements

Repeatability plot for each unit, after a joint drift inversion, is shown:



Standard deviations of each unit are (in μGal): U10: 3.0, U11, 4.1, U12: 5.8, U13: 3.0.
Unit 11 has an about 20 μGal diurnal variation.
Measurement repeatability (standard deviation) is <2.5 μGal.



Average and standard deviation of sensor residuals as each station:


The values for this plot are on the Google drive.

7. Long-term forecast
Completion of the main survey tomorrow Sunday 27th September at around 8:00.
Gradient measurements at Schildmeer and Usquert to be done Monday.
Gradient measurements at Winsum to be done Tuesday.
Possibly a day of calibration Gasselte – Zwolle – Maastricht.

8. Weather forecast next 24 hours
4-17oC, sunny and clear in the day, cold at night

9. Areas of concern
None.

23.23 September 27th

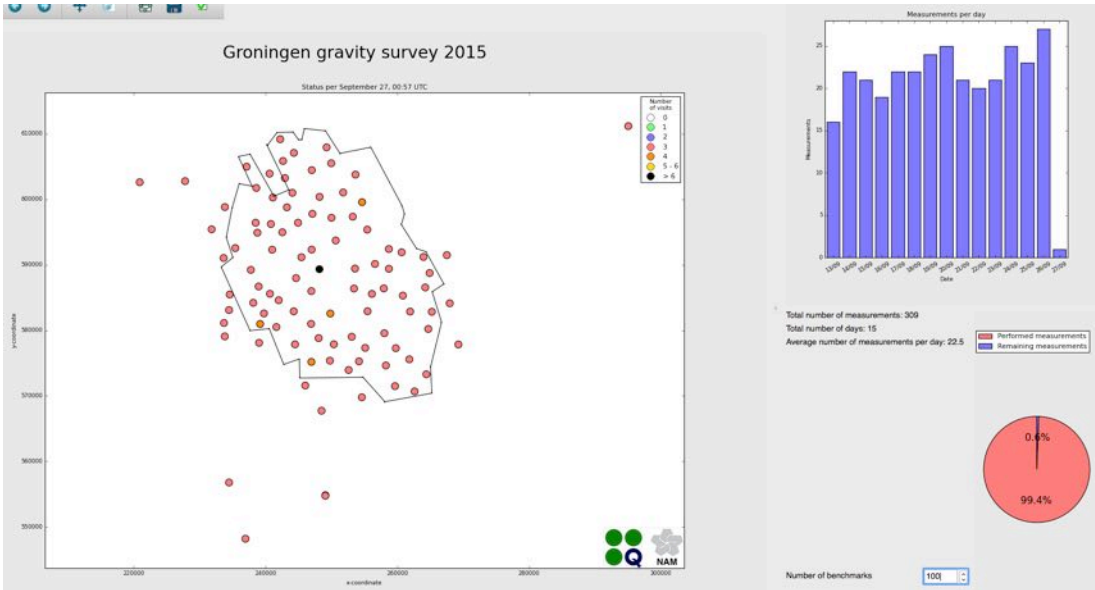
1. Ongoing activity
Preparing for gradient measurement at 14 Winsum.

2. HSE
Insident report: Cofee thermos fell out of the van (survey vehicle). Interior glass liner shattered. Contents spilled, broken glass remained inside thermos. This happened 23rd September, at site 101. New metal thermos is better secured.

3. Activities last 24 hours (until 8:00)
22 measurements at stations 135, 148, 306, 518, 110, 302, 105, 203, 161, 15, 113, 104, 109, 17, 115, 146, 202, 303, 144, 155, 211, 404. This completes the main survey.
Scouting at Maastricht and Zwolle. Both sites from 1999 are unaltered and suitable for measurements.

4. Planned activities next 24 hours
Gradient measurements as 14 Winsum,
After Action Review meeting at 16:00 in Ten Boer.

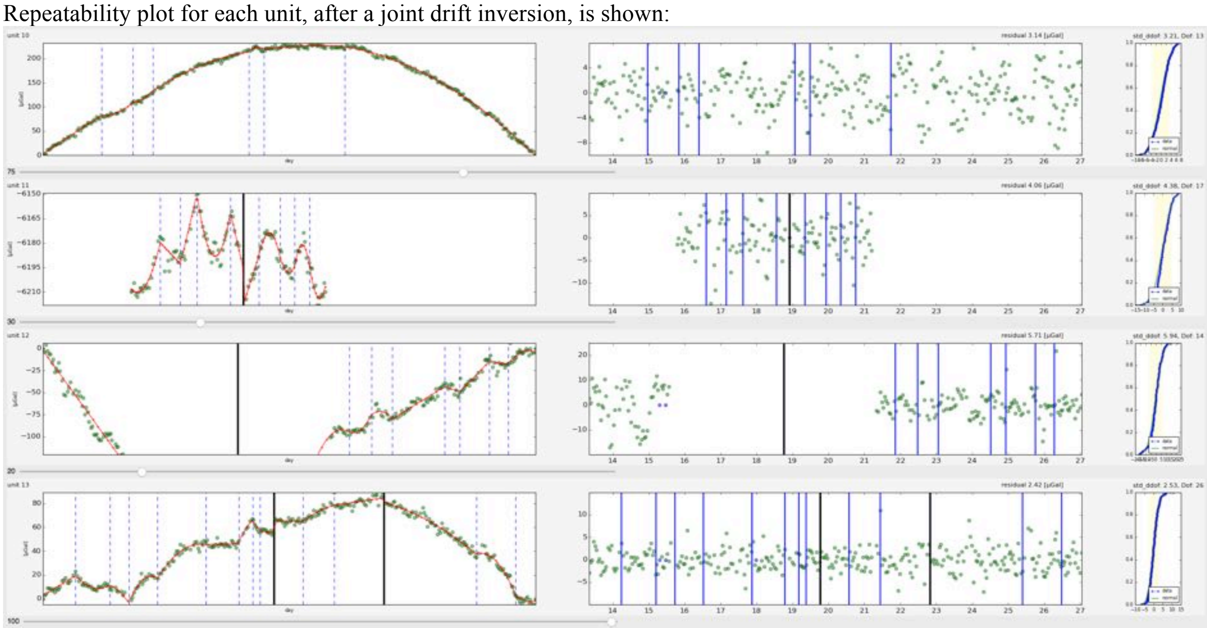
5. Overall progress
309 station measurements out of 309; 100% completed
8 gradient stations out of 11
3:15 hours technical downtime
1:00 hours waiting for NAM personell



Final status plot.

6. Accuracy of measurements

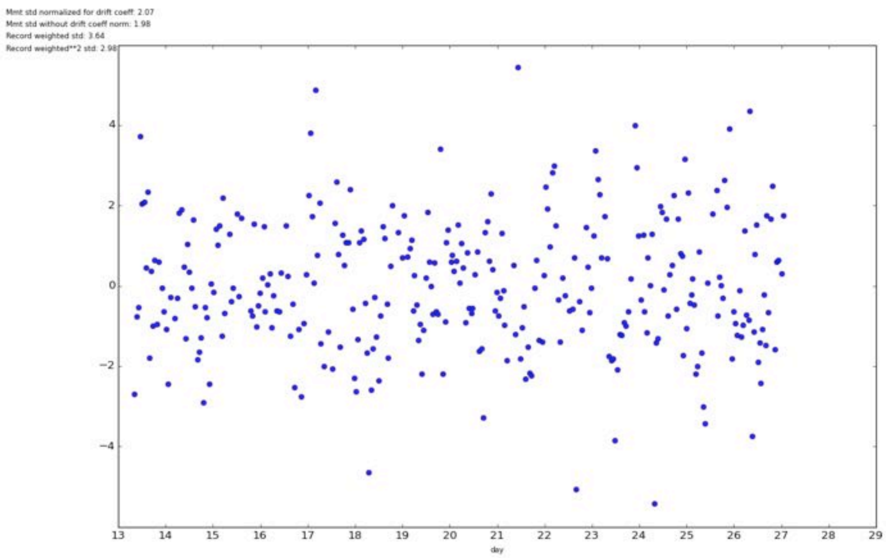
Repeatability plot for each unit, after a joint drift inversion, is shown:



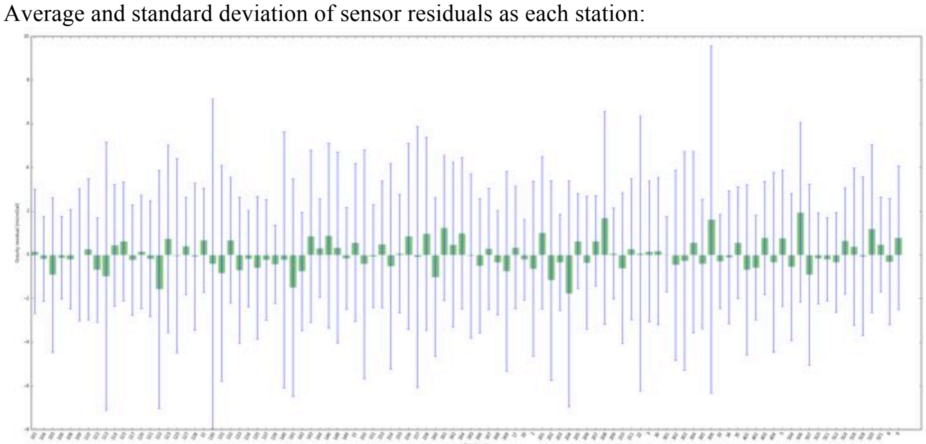
Standard deviations of each unit are (in Gal): U10: 3.2, U11, 4.4, U12: 5.9, U13: 2.5.

Unit 11 has an about 20 Gal diurnal variation.

Measurement repeatability (standard deviation) is 2.1 Gal.



Average and standard deviation of sensor residuals as each station:



7. Long-term forecast
Gradient measurements at Winsum to be done Sunday.
Gradient measurements at Schildmeer and Usquert to be done Monday.
Calibration Gasselte – Zwolle – Maastricht – Gasselte Tuesday evening.
8. Weather forecast next 24 hours
5-17°C, sunny and clear in the day, cold at night.
9. Areas of concern
None.

23.24 September 28th

1. Ongoing activity
Preparing for gradient measurement at 21 Usquert.
2. HSE
Incident report: Van got stuck in soft field at station 14 Winsum. Happened when turning around on the way out after the measurements. Initial inspection did not reveal the soft layer underneath the firm top. A tow truck pulled the survey van out of the soft field.
3. Activities last 24 hours (until 8:00)
Gradient measurement at 14 Winsum.
After Action Review meeting in Ten Boer.
4. Planned activities next 24 hours

Gradient measurements as 21 Usquert and 10 Schildmeer.
Measurement of water height in some selected canals close to sites.

5. Overall progress

309 station measurements out of 309; 100% completed
8 gradient stations out of 11
3:15 hours technical downtime
1:00 hours waiting for NAM personnel

6. Accuracy of measurements

The 3 measurements on 514 and two on 14 show good agreement; within about 1 Gal.

7. Long-term forecast

Gradient measurements at Schildmeer and Usquert to be done Monday.
Calibration Gasselte – Zwolle – Maastricht – Gasselte Tuesday evening.

8. Weather forecast next 24 hours

6-17^{o}C, partly sunny.

9. Areas of concern

None.

23.25 September 29th

1. Ongoing activity

Preparing for scale factor calibration measurement range to Maastricht.

2. HSE

None

3. Activities last 24 hours (until 8:00)

Gradient measurement at 21 Usquert and 10 Schildmeer (Joel and Michael).
Meeting with Jan den Besten in Waterschap Hunze en Aa's, and measurement of water height in ditches near selected stations. Measurements of OM heights (Ola and Snorre).

4. Planned activities next 24 hours

Scale factor calibration measurements Gasselte – Zwolle – Maastricht, scheduled from 17 to 05 Wednesday morning.

5. Overall progress

309 station measurements out of 309; 100% completed
11 gradient stations out of 11
3:15 hours technical downtime
1:00 hours waiting for NAM personnel

6. Accuracy of measurements

The measurements on old and new stations show 1-2 Gal standard deviation, after a linear drift fit.

7. Long-term forecast

Equipment that goes back to US will be packed Wednesday and Thursday, and sent on Friday.

8. Weather forecast next 24 hours

5-17^{o}C, mostly clear skies and sunny.

9. Areas of concern

None.