Block CN05 (Central North 05)

GRAV-D Airborne Data Release User Manual

Applies to Data Release BETA #1, 12/2017

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Version Notes

12/2017 BETA #1: First release

Introduction to GRAV-D and Data User Manuals

NOAA's National Geodetic Survey (NGS) launched the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) program in 2007. This program is designed to replace the current national vertical datum (NAVD 88) with a datum based upon a gravimetric geoid by 2022. To produce the geoid with 1-2 cm accuracy (where possible), an airborne campaign has been launched to measure the gravity field over all of the US and its holdings.

A more comprehensive description of the GRAV-D project is available in the "GRAV-D General Airborne Gravity Data User Manual." The version of that manual that applies to this release is manual v. 2.X. That manual also describes general details of the nominal airborne field operations, data post-processing software specifics, data naming schemes and distribution, data formats, and how to calculate other commonly-used gravity values from the released data. This manual relates details for this block of data that are in addition to the General User Manual.

GRAV-D uses some specific terminology (e.g. "block" for a geographic area with enough flown data and tie lines to provide error statistics, and "survey" for an occupation by the field team of a particular airport, at a particular time, and with a particular aircraft and instrument suite). For a full list of terminology, refer to the Glossary in the Appendices of the "GRAV-D General Airborne Gravity Data User Manual."

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1. Block Description

GRAV-D Block **CN05** is located in the **C**entral Time Zone, in the **N**orth half (south of 40° latitude). This was the fourth (**05**) block of data completed in that region. Block CN05 is 462 km by 340 km, covering areas of Iowa, Nebraska, Minnesota, North Dakota and South Dakota (Figure 1). The corner coordinates defining Block CN05 are listed in Table 1.

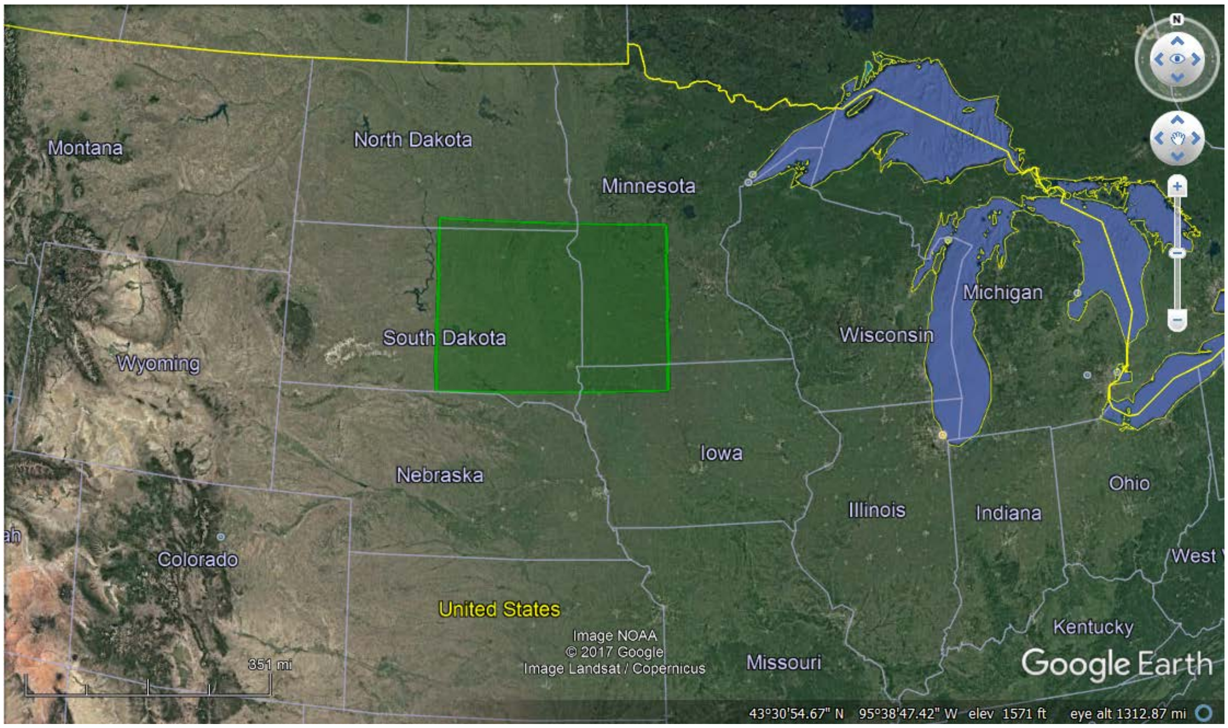


Figure 1: Google Earth Image of the Location of Block CN05

Table 1: Latitude and Longitude Coordinates of Corner Points Defining Block CN05

Latitude (decimal degrees)	Longitude (decimal degrees)
46.136122573	-100.159071472
43.025518086	-100.073033983
43.048005478	-94.334687037
46.024847342	-94.261659483

2. Survey Design and Execution

Airborne gravity data in Block CN05 were collected during two surveys: MN15-2 (Minnesota 2015, second occupation) and MN16-1 (Minnesota 2016, first occupation). All data and cross flights were done at approximately 20,000 ft with the same aircraft but different relative gravimeters. Supplementary data from transit (target of opportunity) flights may be made available at a future date. Table 2, Table 3, and Table 4 give a synopsis of survey layout and execution for the data. Figure 2: shows the data coverage, plotted in Google Earth.

In CN05 all data lines are East-West and cross lines are North-South. The block consists of 21 data lines from MN15-2; and 19 data lines and 6 cross lines from MN16-1. Data lines 105 and 127 from MN15-2 were repeated in MN16-1 and are designated line numbers 205 and 227. Both 105 and 127 are partial lines and 205 and 227 are complete. The usual line numbering scheme used by GRAV-D (see "General User Manual") was used for this survey. In the data file, line numbers are preceded by the block name (i.e. CN05101= block CN05's line 101).

Table 2: Survey Overview

Conducting Organization	NOAA- National Geodetic Survey	
Survey Name	MN15-2	MN16-1
Airport Base of Operations	Flying Cloud Airport (FCM) Eden Prairie, MN FBO: Executive Aviation	Flying Cloud Airport (FCM) Eden Prairie, MN FBO: Executive Aviation
Geographic Location	Iowa, Michigan, Minnesota, and Wisconsin	
Dates of Airborne Operations	Aug. 9 – Sep. 13, 2015	Jul. 28 – Aug. 31, 2016

Table 3: Aircraft and Instrumentation

Aircraft	NOAA Turbo Commander (N45RF)
Engines, number and type	2, Truboprop
Gravity Instrumentation	MN15-2 Micro-g LaCoste (MGL) TAGS S-161 (relative) MN16-1 Micro-g LaCoste (MGL) TAGS S-137 (relative) MGL A-10 (absolute) LaCoste and Romberg D-43 and G-6 (relative)
GPS Instrumentation	NovAtel DL-4 Plus NovAtel SPAN-SE with Honeywell µIRS (GPS + IMU)

Table 4: Survey Design and Execution

Line Spacing	Data Lines: 10 km Cross Lines: ~80 km
Type of Layout	Regular data lines & regular cross lines
Nominal Survey Altitude	20,000 ft
Nominal Aircraft Ground Speed	250 knots
Number of Lines Released	Data Lines: 21 (MN15-2), 19 (MN16-1) Cross Lines: 6 (MN16-1) Repeat Lines: 2
Number of Crossovers	226

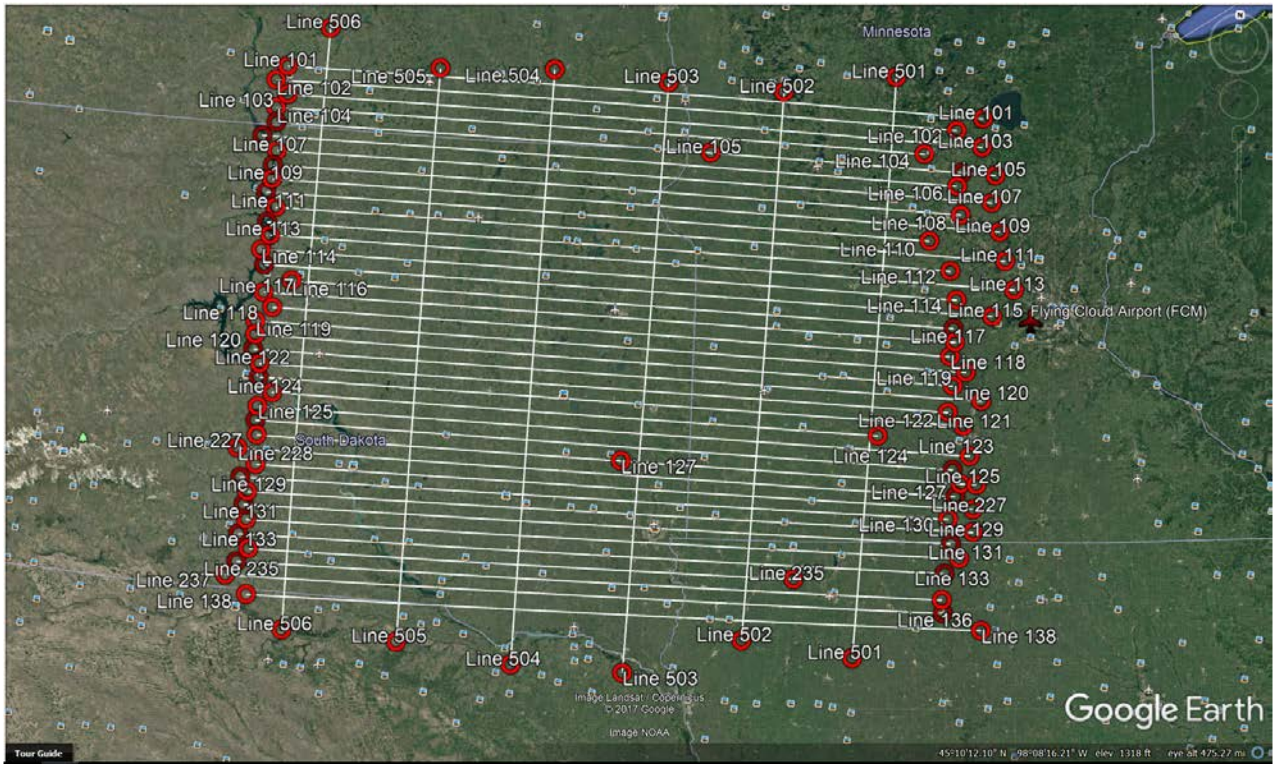


Figure 2: Data Coverage for CN05. Data lines start in the north and range from 101 to 138 (All flights flown from Flying Cloud Airport, Eden Prairie, MN.) Airport marked with a red star.

2.1 GPS/IMU Instrumentation

The NOAA Turbo Commander had one GPS antenna available for scientific measurements. Two geodetic-quality GPS receivers shared the antenna: one NovAtel DL-4 Plus (included as part of the TAGS gravimeter timing unit) and a NovAtel SPAN-SE. The NovAtels' had a data rate of 1 Hz. The NovAtel SPAN-SE system included a Honeywell Inertial Measurement Unit (IMU) that recorded aircraft orientation information at 200 Hz during the flight, including pitch, roll, yaw, and heading.

On the ground, two Ashtech Z-Surveyor antenna/receivers for MN15-2, recording at 1 Hz served as GPS base stations throughout the survey. For MN16-1 two NovAtel PP6 were used. See Section 3.2.1 for a table of GPS data available for each flight and processing details.

2.2 Gravity Instrumentation

The Micro-g LaCoste TAGS (Turn-key Airborne Gravimetry System) was mounted in the cargo area of the Turbo Commander. The TAGS records data at 1 Hz and has a NovAtel timing unit mounted on the gravimeter. The gravimeter also records an environmental file at 0.1 Hz. For more information on the instrument, refer to its user manual (Micro-g LaCoste, 2010).

The TAGS was mounted to the seat tracks in the center of the fuselage of the aircraft. The IMU was mounted on top of the TAGS and in the center of the frame. Table 5 lists the lever arm measurements between the TAGS and other instruments (distances are measured along the body of the aircraft: X positive toward the right, Y positive toward the nose, and Z positive up.)

Table 5: MN15-2 Lever Arm Measurements FROM the SPAN TO the Other Instruments

Instrument/Location	X (m)	Y (m)	Z (m)
Gravimeter (TAGS 161)	-0.017	0.019	-0.433
Aircraft GPS Antenna	0.092	0.143	0.616

Table 6: MN16-1 Lever Arm Measurements FROM the SPAN TO the Other Instruments

Instrument/Location	X (m)	Y (m)	Z (m)
Gravimeter (TAGS 137)	-0.011	0.015	-0.527
Aircraft GPS Antenna	0.092	0.143	0.616

3. GPS and Gravity Data Processing

3.1 Whole-Survey Applicable Details

3.1.1 GPS

Table 7: GPS High Rate Data Availability (1 Hz or higher)

Airport	Type	Receiver	Flight Available	Day of Year Available (UTC)
MN15-2 FCM	Kinematic	NovAtel (SPAN)	f10, f12, f16-f18, f24, f28	231, 232, 245, 246, 252, 255
		Ashtech East	f10, f12, f16-f18, f24, f28	231, 232, 245, 246, 252, 255
		Ashtech WEST	f10, f17-f18, f28	231, 245, 246, 255
MN16-1 FCM	Kinematic	NovAtel (SPAN)	f10, f14, f16, f18, f21, f23, f25, f27, f28, f31	214, 218-220, 222, 226, 227, 228, 234, 237
	Static	Ashtech North	f10, f14, f16, f18, f21, f23, f25, f27, f28, f31	214, 218-220, 222, 226, 227, 228, 234, 237
		Ashtech South	f10, f14, f16, f18, f21, f23, f25, f27, f28, f31	214, 218-220, 222, 226, 227, 228, 234, 237

Data were processed using GRS80 and ITRF08. After post-processing the GPS-only kinematic data (before processing with coupled IMU), average position accuracy for the data block is calculated. Position standard deviation is estimated by the GPS processing programs for each flight and those numbers are averaged to provide a survey-wide estimate of GPS position accuracy. For the data lines, the average horizontal position accuracy is ±0.053 m and the average vertical position accuracy is ±0.087 m (95% confidence interval).

3.1.2 Ground Gravity Tie

Updated absolute gravity measurements were performed by NGS with a Micro-g LaCoste A-10 gravimeter in September of 2015. The A-10 was set up at the exact location of the aircraft, Dynamic Aviation's King Air. The positions were determed from the GPS collected during the gravity survey while the plane was parked. At Flying Cloud Airport, the location is designated as KFCM TAGS (44.82422686°N, 93.45237376°W) and it has an absolute gravity value of 980572.819 ± 0.008 mGal at 80.6 cm above the tarmac.

3.1.3 Gravity Filtering

For block CN05, flights were accomplished in two surveys and were filtered the same way. Newton v1.4 uses a time-domain Gaussian filter that is applied three times to the data during final filtering. The Gaussian filter chosen for this survey has a 6-sigma of 120s, i.e. a 2-sigma of only 40s. Applying the filter three times provides superior noise reduction compared to a single application of the filter. Although the triple application provides better noise reduction, the filter is tailored to best preserve the amplitudes of the long wavelength signal, while allowing some short wavelength noise to remain in the final product. For suggestions on data handling, including on further noise suppression, see Section 4.1 Suggested Data Handling.

3.2 Whole-Block Applicable Details

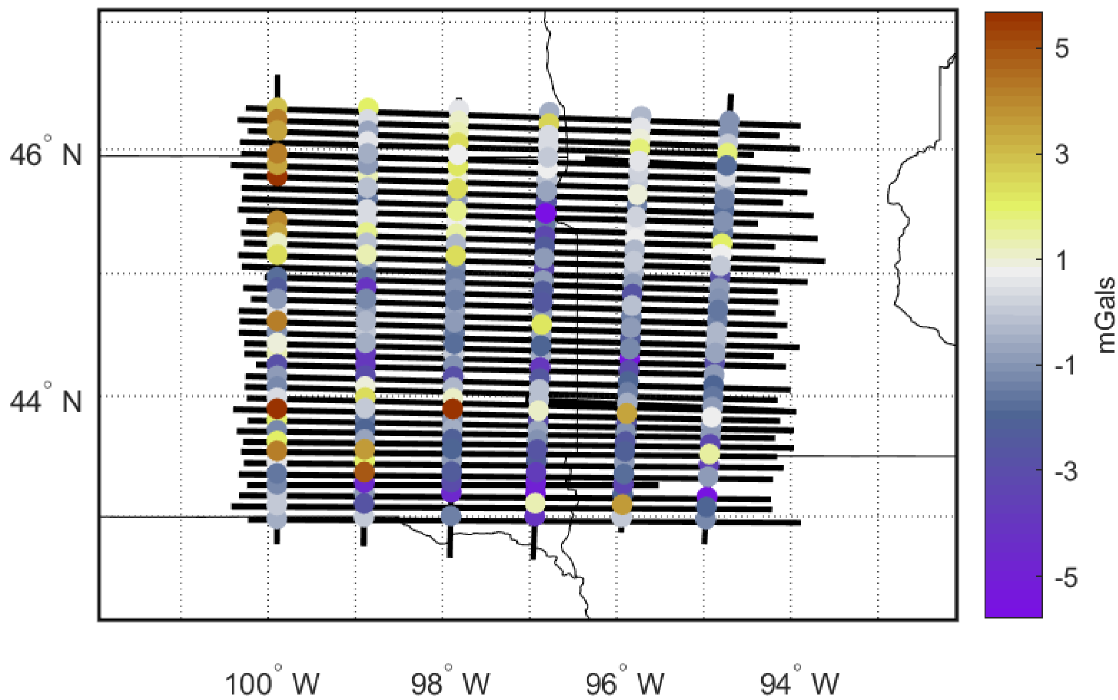
3.2.1 Gravity Error Analysis

Crossover error analysis was done by identifying the crossing points of the data lines and cross lines and then applying the standard free-air correction to bring all points to the average altitude of the block. There was an unidentified bias in all flight lines, so an additional correction was applied before the crossover analysis to adjust each line's median airborne gravity value to the median gravity value of EGM08 along the line. The bias-corrected difference between the cross line gravity value and data line gravity value is the residual. The square root of the RMS of the residuals yields the total RMS error. For CN05, the result of the crossover analysis is shown in Table 9 and in Figure 3.

Table 8: Gravity Crossover Error Analysis

Nominal Altitude (ft)	Nominal Altitude (m)	Altitude for Analysis (m)	Number of Crossovers	RMS Of Residuals (mGal)	Std. Dev. Of Residuals (mGal)	Mean Crossover Difference (mgal)	RMS Error (mGal)
20,000	6,096	6,329	226	2.15	2.10	-0.51	1.52

One assumption of crossover analysis is that the quality of the cross lines are high and that the crossover difference reflects only the error in the data lines. This is not necessarily the case. This means that the crossover statistics do not accurately reflect the quality of the data lines, due to the errors in the cross lines. One way to quantify this problem is by reporting the standard deviation and mean of the crossover residuals for each cross line, as in Table 10. The higher the standard deviation of the residuals, the more likely that the cross line was noisy. Also, a non-zero mean could indicate a cross-line bias with respect to the data lines (unlikely here because of the bias correction applied), which would produce false crossover statistics that indicate poor data line quality.



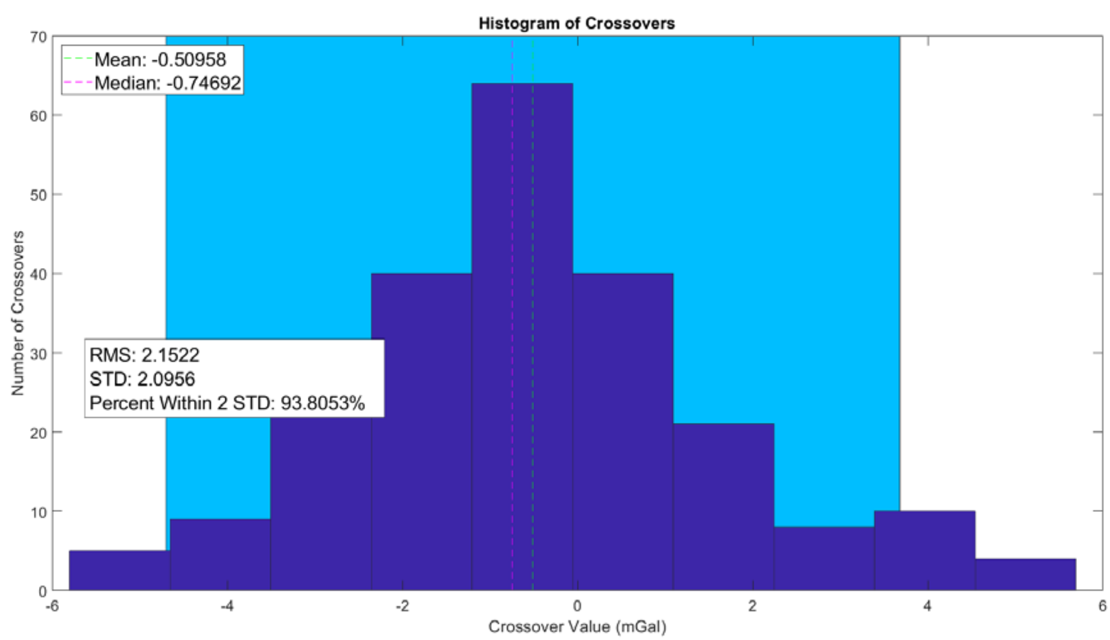


Figure 3: Crossover Residuals, Histogram, and Statistics for Block CN05.

Table 9: Quality of Cross Lines Used in Crossover Analysis

Cross Line Number	Standard Deviation of Residuals Along Line (mGal)	Mean of Residuals Along Line (mGal)
501	1.47	-1.07
502	1.74	-0.77
503	1.99	-1.52
504	1.93	-0.25
505	2.06	-0.38
506	2.41	1.23

Another way to evaluate the quality of gravity data is to calculate the correlation of the gravity values along two adjacent data lines. Average correlation and statistics on the spread of correlations can yield information about the quality of the data lines (Table 11) This technique works well as a measure of data quality in areas with little lateral variability in the gravity field (such as the Gulf of Mexico). But the technique doesn't work well when the correlations are not expected to be high, such as in areas with large changes in topography and/or density from data line to data line. Line correlations were calculated for adjacent lines and then averaged to give an overall quality measurement. Correlations > 80% mean the lines are very highly correlated, 70% - 80% mean the lines are highly correlated, 50% - 70% mean the lines are more correlated than not, and <50% are more uncorrelated than correlated.

Table 10: Average Data Line Correlation

Number of Correlations	Average Data Line Correlation	Standard Deviation of Correlations
43	91.60%	6.37%

A fourth way of gauging data quality is by calculating the repeatability of the gravity signal along reflown lines of good quality. Reflight analysis can also help to pinpoint the lightest filtering that produces highly-correlated results. In CN05 two lines were at least partially re-flown: CN05105 and CN05205, and CN05127 and CN05227. The correlations between these re-flown lines are found in (Table 11).

Table 11: Correlations between reflown lines

Survey	Line Track Number	Correlation
MN16-1	105	97.74%
MN16-1	205	
MN15-2	127	97.34%
MN16-1	227	

3.3 Flight- and Line-Specific Details

3.3.1 GPS processing- by flight

GPS data were processed in Inertial Explorer (IE) v. 8.7. A lever arm correction (to move the position solution from that of the GPS antenna to that of the center of the gravimeter) was applied within the IE software and included in the GPS+IMU solution. In the case of the GPS-only solution, no IMU data were available and a translation-only, vertical lever arm correction was instead applied by the Newton gravity code to translate the GPS-only positions to the center of the gravimeter.

NGS has developed an independent method of measuring the quality of GPS position solutions based on information available from both Inertial Explorer. For the GPS-only part of the position solution, the quality analysis takes into account the following: whether a fixed or float solution was achieved, the magnitude of the combined separation between forward and reverse solutions (a measure of precision), and the estimated position accuracy. For details on the calculation, please refer to the “GRAV-D General Airborne Gravity Data User Manual.”

3.3.2 Gravity processing- by line

All gravity processing was done with NGS’ Newton v1.4 software. For a description of the package, refer to the “GRAV-D General Airborne Gravity Data User Manual.” The final gravity data file contains full-field gravity at altitude (Figure 5), although other gravity products such as free-air anomalies or free-air disturbances (Figure 6) can be easily calculated by following directions in Section 4 of the “GRAV-D General Airborne Gravity Data User Manual”.

Table 12: GPS+IMU and GPS-only Kinematic Processing Results

Survey	Flight Num.	Rover GPS Unit	Solution Type	Elevation Mask (deg)	Line Num.	NGS Quality Grade
MN15-2 FCM	10	SPAN	GPS+IMU	7.5	127	100
					235	100
					136	100
	12	SPAN	GPS+IMU	5	123	100
					124	100
					125	100
					126	100
	16	SPAN	GPS+IMU	7.5	121	100
					122	100
	17	SPAN	GPS+IMU	7.5	119	100
					120	100
	18	SPAN	GPS+IMU	5	115	100
					116	100
					117	100
					118	100
	24	SPAN	GPS+IMU	7.5	133	100
					134	100
	28	SPAN	GPS+IMU	7.5	129	100
					130	100
					131	100
					132	100
MN16-1 FCM	10	SPAN	GPS+IMU	5	506	100
					903	100
	14	SPAN	GPS+IMU	7.5	111	100
					112	100
					113	100
					114	100
	16	SPAN	GPS+IMU	5	101	100
					102	100
					103	100
					104	100
	18	SPAN	GPS+IMU	7.5	109	100
					110	100
	21	SPAN	GPS+IMU	5	105	100
					503	100
					505	100
	23	SPAN	GPS+IMU	5	107	100
					108	100
	25	SPAN	GPS+IMU	5	501	100
					502	100
					504	100
	27	SPAN	GPS+IMU	7.5	138	100
	28	SPAN	GPS+IMU	5	106	100
					128	100
					205	100
					227	100
	31	SPAN	GPS+IMU	5	237	100

Table 13: Gravity Processing Results

Survey	Flight Num.	Line Num.	Time of Deleted Data Section (s)	Comments
MN15-2 FCM	10	127		
		235		
		136	63981-64174	Bump removed
	12	123		
		124	70587-70816	Bump removed
		125		
		126		
	16	121		
		122		
	17	119		
		120		
	18	115	44179-44386	Bump removed
		116		
		117		
		118		
	24	133		
		134		
	28	129		
		130		
		131		
		132		
MN16-1 FCM	10	506	66434-66531, 66719-66957	Bump removed
	14	111		
		112		
		113		
		114		
	16	101		
		102		
		103		
		104		
	18	109		
		110		
	21	105		
		503		
		505		
	23	107		
		108		
	25	501		
		502		
		504		
	27	138		
	28	106		
		128		
		205		
		227		
	31	237	46933-47057	Bump removed

Table 14 Bias from EGM08 by Line

Survey	Flight Num.	Line Num.	Bias from EGM08
MN15-2 FCM	10	127	2.88
		136	4.88
		235	4.34
	12	123	3.36
		124	3.9
		125	2.89
		126	1.89
	16	121	2.61
		122	1.67
	17	119	2.15
		120	0.81
	18	115	2.17
		116	1.73
		117	2.85
		118	1.34
	24	133	1.85
		134	2.31
	28	129	2.48
		130	1.81
		131	2.34
		132	1.17
MN16-1 FCM	10	506	2.37
	14	111	0.79
		112	-0.63
		113	1.04
		114	-0.4
	16	101	0.49
		102	-0.27
		103	0.2
		104	-1.1
	18	109	1.52
		110	0.86
	21	105	0.81
		503	-0.06
		505	1.24
	23	107	1.17
		108	-0.68
	25	501	0.39
		502	0.65
		504	0.73
	27	138	1.1
	28	106	-0.52
		205	0.92
		227	0.39
		228	-1.56
	31	237	0.56

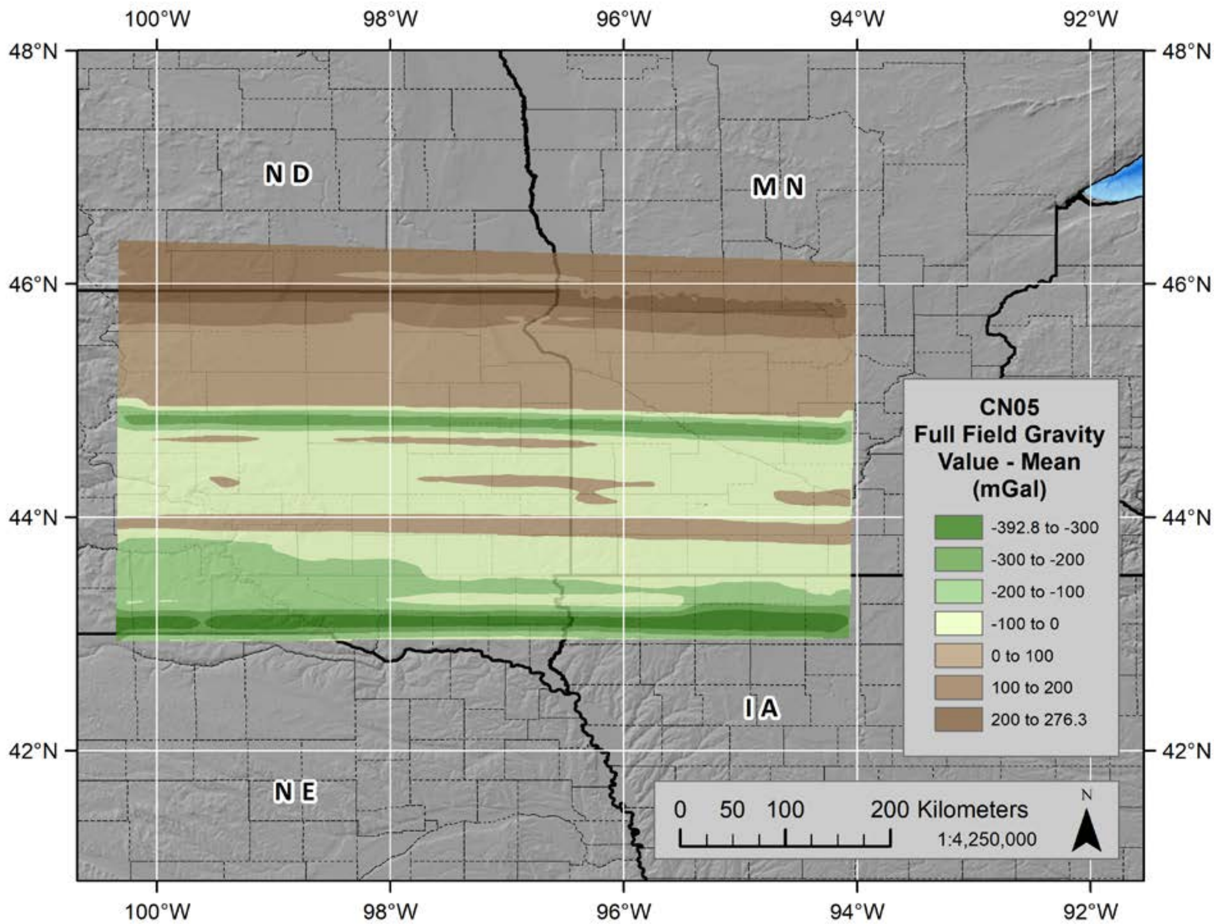


Figure 4: Full-field gravity at altitude (mean removed) for Block CN05. This is the data in the gravity release ".txt" file and includes the effects of differing altitudes along flight lines.

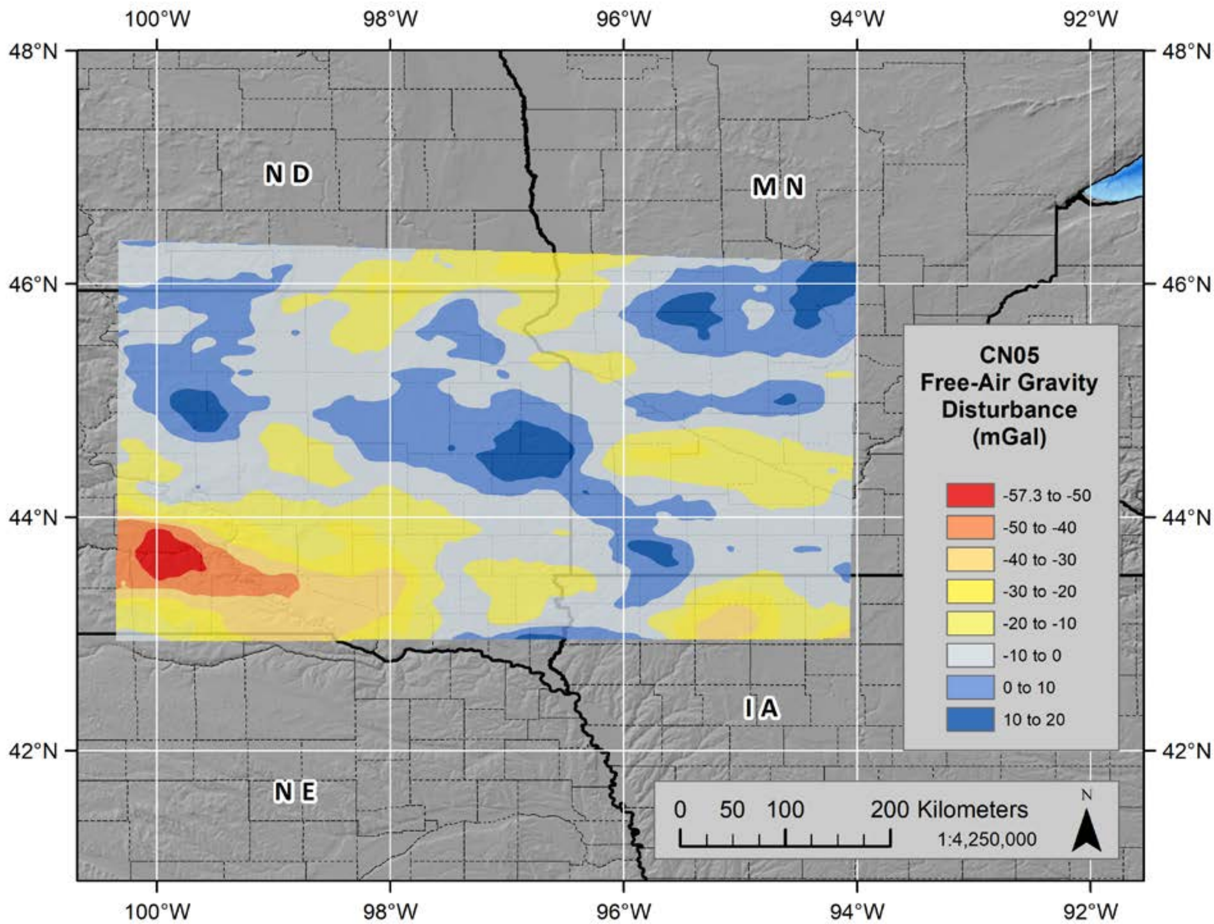


Figure 5: Free-air gravity disturbance for Block CN05 with respect to the GRS80 ellipsoid.

4. Data Usage Guidelines

4.1 Suggested Data Handling

This data product was purposefully filtered to preserve the amplitude of the long-wavelength gravity signal. As a trade-off, the filter allows some short wavelength noise to remain in the product. Prior to use for geophysical purposes, the data should be run through a frequency-domain low-pass filter to remove that excess short wavelength noise. For geodetic purposes, higher frequencies can be damped during inclusion into a spherical harmonic model. In any case where downward continuation will be done with this data, the high frequency noise should first be filtered out, damped, or otherwise dealt with so that the downward continuation does not amplify the noise.

4.2 Documentation

The survey block User Manual, the general GRAV-D User Manual, and metadata for the block should all be downloaded with the data and kept in the same directory. The contents of the manuals are critical to understanding the quality of the data and using the data properly.

4.3 How to Cite These Data

The following citations should be used in all presentations or publications that reference the GRAV-D work. Please replace the *DATE* tag in the following references with the date you downloaded the data or reports from the NGS website.

The GRAV-D Team, in alphabetical order, are: Vicki A. Childers, Justin Dahlberg, Theresa M. Damiani, Jeff Kanney, Jeffery A. Johnson, Chris Villarreal, Derek van Westrum, and Monica A. Youngman.

To reference the CN05 data file, reference the webpage:
GRAV-D Science Team (2017). “Gravity for the Redefinition of the American Vertical Datum (GRAV-D) Project, Airborne Gravity Data; Block CN05”. Available *DATE*. Online at: http://www.ngs.noaa.gov/GRAV-D/data_CN05.shtml

To reference the block and survey details, reference the block user manual:
GRAV-D Science Team (2017). “Block CN05 (Central North 05); GRAV-D Airborne Gravity Data User Manual.” Monica A. Youngman and Jeffery A. Johnson, ed. Version BETA. Available *DATE*. Online at: http://www.ngs.noaa.gov/GRAV-D/data_CN05.shtml

To reference the general GRAV-D project operations, reference the General User Manual:
GRAV-D Science Team (2017). “GRAV-D General Airborne Gravity Data User Manual.” Theresa Damiani, Monica Youngman, and Jeffery Johnson, ed. Version 2.1. Available *DATE*. Online at: http://www.ngs.noaa.gov/GRAV-D/data_products.shtml

5. References

Micro-g LaCoste, 2010. “TAGS Turnkey Airborne Gravity System AIR III Hardware & Operations Manual.”