Block ES10 (Eastern South 10)

GRAV-D Airborne Data Release User Manual

Applies to Data Release BETA #2, 2/2018

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Version Notes

2/2018 BETA #2: Second release (Corrects data processed without TAGS S-211 Calibration factor.

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 **ES10** is located in the **E**astern Time Zone, in the **S**outh half (south of 40° latitude). This was the tenth (**10**) block of data completed in that region. Block ES10 is 350 km by 410 km, covering parts of Georgia, Kentucky, North Carolina, South Carolina, Tennessee, Virginia, and West Virginia (Figure 1). The corner coordinates defining Block ES10 are listed in Table 1.

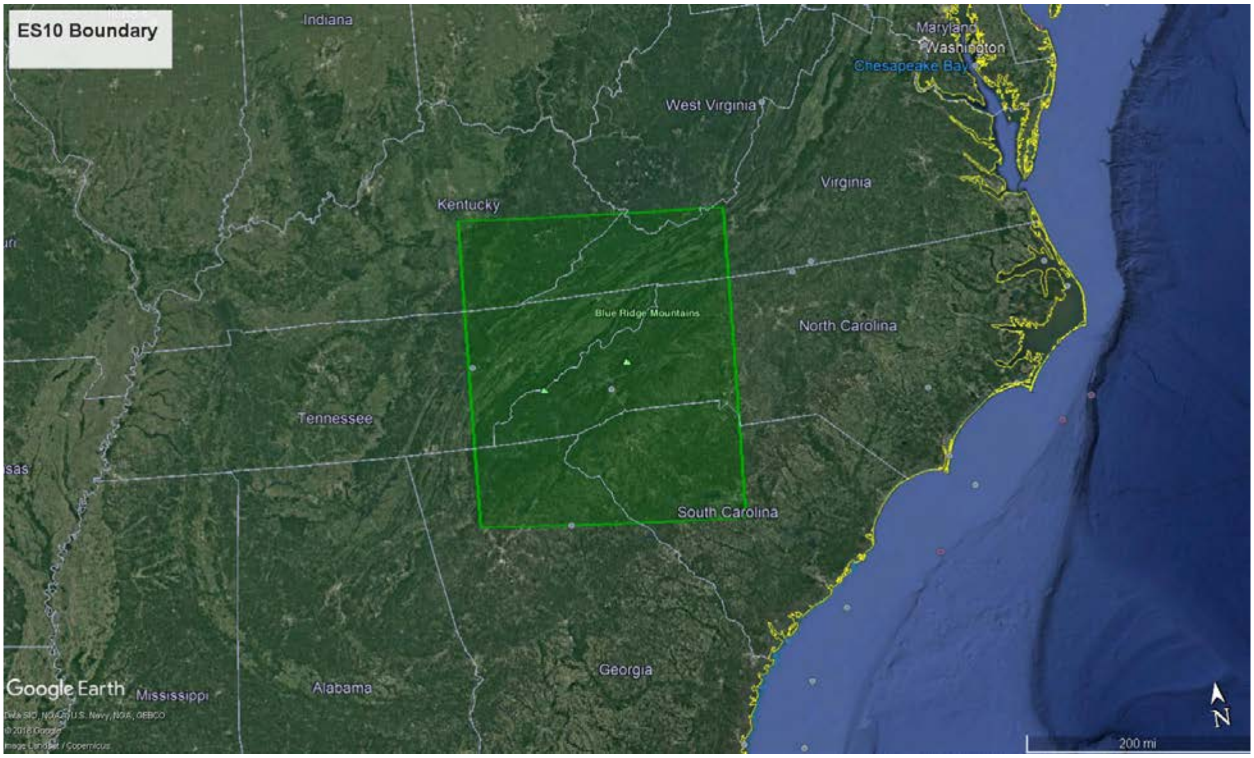

Figure 1: Google Earth Image of the Location of Block ES10

Table 1: Latitude and Longitude Coordinates of Corner Points Defining Block ES10

Latitude (decimal degrees)	Longitude (decimal degrees)
37.570480459	-84.434744436
34.550706318	-84.846202970
34.192447036	-80.952677098
37.383625202	-80.529527013

2. Survey Design and Execution

Airborne gravity data in Block ES10 were collected during two surveys: NC17-1 (North Carolina 2017, first occupation), and NC17-2 (North Carolina 2017, second occupation). Data lines from both surveys were flown at approximately 18,000 ft. ES10 was surveyed with one aircraft and one relative gravimeter. 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 ES10, data lines are East-West and cross lines are North-South. The block consists of 36 data lines and 2 cross lines from NC17-1, and 9 data lines and 3 cross lines from NC17-2. Four pairs of data lines were flown twice with acceptable data: Line ES10104 from NC17-1 and line ES10204 from NC17-2; line ES10108 from NC17-1 and line ES10208 from NC17-2, line ES10127 from NC17-1 and ES10227 from NC17-2, and line ES10228 from NC17-1 and line ES10328 from NC17-2. 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. ES10101= block ES10's line 101).

Table 2: Survey Overview

Coducting Organization	NOAA- National Geodetic Survey	
Survey Name	NC17-1	NC17-2
Airport Base of Operations	Smith Reynolds Airport (INT) Winston-Salem, NC FBO: Landmark Aviation	Smith Reynolds Airport (INT) Winston-Salem, NC FBO: Landmark Aviation
Geographic Location	Kentucky, Georgia, North Carolina, South Carolina, Tennessee, Virginia, and West Virginia.	
Dates of Airborne Operations	Mar 16 - Apr 11, 2017	Sep 13 - Sep 18, 2017

Table 3: Aircraft and Instrumentation

Aircraft	Aurora Flight Sciences Centaur (N49AU)
Engines, number and type	2, Turboprop
Gravity Instrumentation	Micro-g LaCoste (MGL) TAGS S-211 (relative) MGL A-10 (absolute) LaCoste and Romberg D-43 and G-6 (relative)
GPS Instrumentation	NovAtel DL-V3 or 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	18,000 ft
Nominal Aircraft Ground Speed	150 knots
Number of Lines Released	Data Lines: 36 (NC17-1), 9 (NC17-2) Cross Lines: 2 (NC17-1), 3 (NC17-1) Repeat Lines: 4 data lines
Number of Crossovers	225

Figure 2: Data Coverage for ES10. Data lines range from 101 to 141. Smith Reynolds Airport (INT) is marked with a red star.

2.1 GPS/IMU Instrumentation

The Centaur had one GPS antenna available for scientific measurements. Two geodetic-quality GPS receivers shared the antenna: either a NovAtel DL-V3 or 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 20 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, one DL-V3 (20 Hz) and one Trimble R7 (1 Hz) served as GPS base stations throughout the NC17-1 survey and one DL-V3 (20 Hz) and one NovAtel PP6 (1 Hz) served as GPS base stations throughout the NC17-2 survey. 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 main compartment of the Centaur (optionally piloted aircraft). The TAGS records data at 20 Hz and has a NovAtel timing unit mounted on the gravimeter. The gravimeter also records an environmental file at 20 Hz. For more information on the instrument, refer to its user manual (Micro-g LaCoste, 2010).

The TAGS S-211 was mounted to the seat tracks on the starboard side of the fuselage. The IMU was mounted to the right of the gravimeter. 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: Lever Arm Measurements FROM the SPAN TO the Other Instruments

Instrument/Location (NC17-1)	**X (m)**	**Y (m)**	**Z (m)**
Gravimeter	-0.300	-0.100	0.300
Aircraft GPS Antenna	-0.356	3.353	-0.051
Instrument/Location (NC17-2)	**X (m)**	**Y (m)**	**Z (m)**
Gravimeter	-0.300	-0.100	0.300
Aircraft GPS Antenna	-0.250	-0.070	0.800

3. GPS and Gravity Data Processing

3.1 Whole-Survey Applicable Details

3.1.1 GPS

Table 6: GPS High Rate Data Availability (1 Hz or higher)

Airport	Type	Receiver	Flight Available	Day of Year Available (UTC)
NC17-1 INT	Kinematic	NovAtel (SPAN)	f01-f16, f18-f21	75, 76, 78-84, 91-94, 97-99, 101
	Static	NovAtel DL-V3	f01-f16, f18-f21	75, 76, 78-84, 91-94, 97-99, 101
		Trimble R7	f01-f16, f18-f21	75, 76, 78-84, 91-94, 97-99, 101
NC17-2 INT	Kinematic	NovAtel (SPAN)	f01-f05	257-261
	Static	NovAtel DL-V3	f01-f05	257-261
		NovAtel PP3	f01-f05	257-261

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 ±0.054 m and the average vertical position accuracy is ±0.087 m (95% confidence interval).

3.1.2 Ground Gravity Tie

Absolute gravity measurements were performed by NGS with a Micro-g LaCoste A-10 gravimeter in March 2017 (INT). The A-10 was set up at the exact location of the aircraft. The positions were determed from the GPS collected during the gravity survey while the plane was parked. Table 7 is a summary of the point ID, location and gravity tie from each of the airports.

Table 7: Gravity Ties at the height of the TAGS Gravimeter in the airplane.

Airport	Point ID	Latitude	Longitude	Tie height above mark (cm)	Gravity Tie (mGal)
INT	KINT TAGS	36.14202938°N	-80.22547403°W	150	979703.167 ± 0.008

3.1.3 Gravity Filtering

For block ES10, 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 ES10, the result of the crossover analysis is shown in Table 8 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	5428	225	2.12	2.10	-0.33	1.51

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 9. 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.

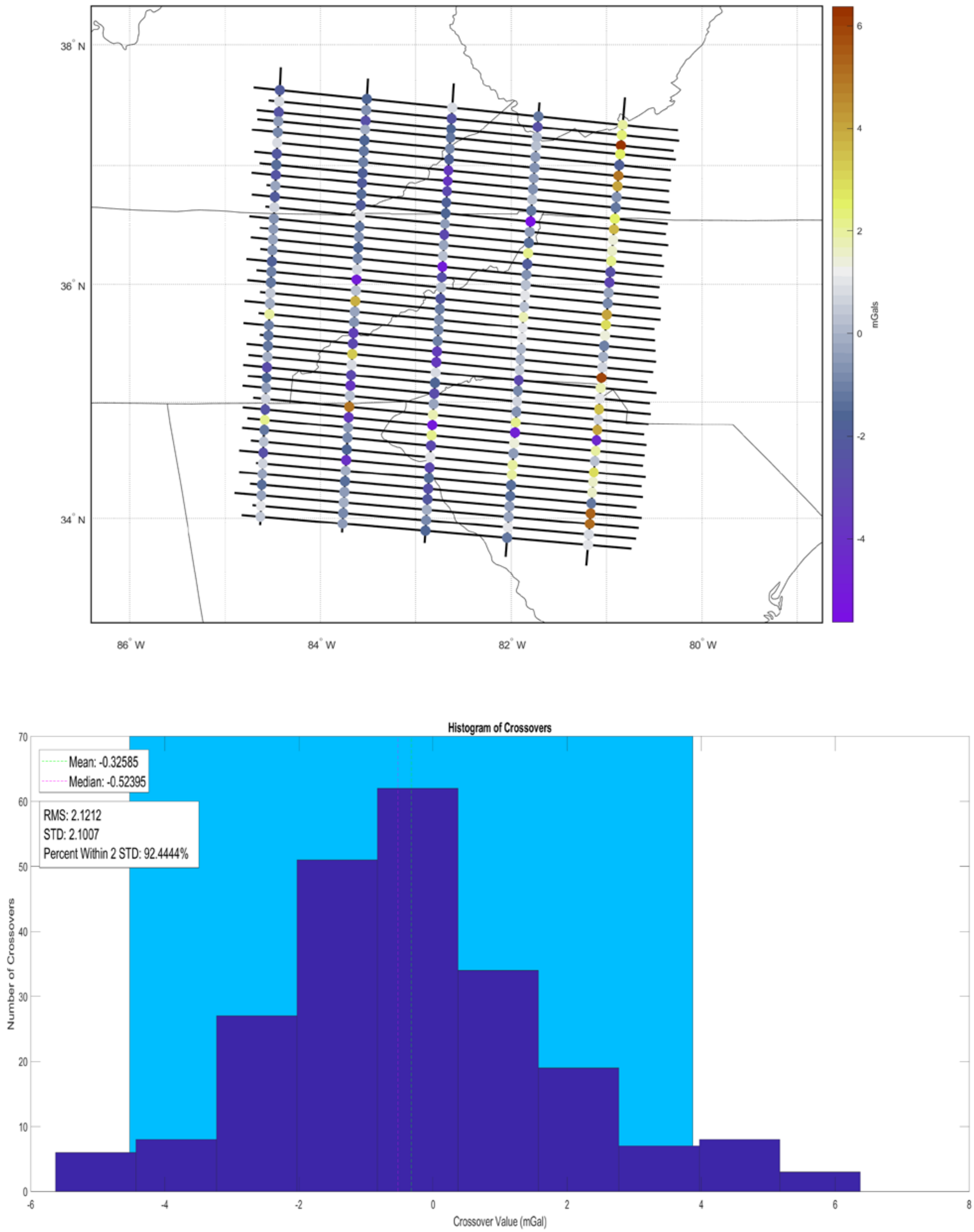

Figure 3: Crossover Residuals, Histogram, and Statistics for Block ES10

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	1.28	-0.57
502	1.97	-0.93
503	1.64	-1.45
504	1.62	-0.27
505	2.48	1.59

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 10) 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
53	93.39%	5.12%

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 ES10 four data lines had re-flights: ES10104, ES10108, ES10127, and ES10128. The correlations between these re-flown lines are found in (Table 11).

Table 11: Correlations between Reflown Lines

<table>
<tr><th>Survey</th><th>Line Track Number</th><th>Correlation</th></tr>
<tr><td>NC17-1</td><td>ES10104</td><td rowspan="2">99.73</td></tr>
<tr><td>NC17-2</td><td>ES10204</td></tr>
<tr><td>NC17-1</td><td>ES10108</td><td rowspan="2">99.67</td></tr>
<tr><td>NC17-2</td><td>ES10208</td></tr>
<tr><td>NC17-1</td><td>ES10228</td><td rowspan="2">99.92</td></tr>
<tr><td>NC17-2</td><td>ES10328</td></tr>
<tr><td>NC17-1</td><td>ES10127</td><td rowspan="2">99.76</td></tr>
<tr><td>NC17-2</td><td>ES10227</td></tr>
</table>

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 4), although other gravity products such as free-air anomalies or free-air disturbances (Figure 5) 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	Rover GPS Unit	Solution Type	Elevation Mask (deg)	Line Num.	NGS Qualtiy Grade
NC17-1 (INT)	1	SPAN	GPS + IMU	5	101	100
					102	100
	2	SPAN	GPS + IMU	5	139	100
					140	100
	3	SPAN	GPS + IMU	5	104	100
	4	SPAN	GPS + IMU	5	105	100
					106	100
	5	SPAN	GPS + IMU	7.5	137	100
					138	100
	6	SPAN	GPS + IMU	5	135	100
					136	100
	7	SPAN	GPS + IMU	5	108	100
	8	SPAN	GPS + IMU	5	109	100
					110	100
	9	SPAN	GPS + IMU	7.5	133	100
					134	100

	10	SPAN	GPS + IMU	7.5	111	100
					112	100
	11	SPAN	GPS + IMU	5	113	100
					114	100
	12	SPAN	GPS + IMU	5	131	100
					132	100
	13	SPAN	GPS + IMU	5	115	100
					116	100
	14	SPAN	GPS + IMU	5	117	100
					119	100
					120	100
	15	SPAN	GPS + IMU	5	121	100
					122	100
					123	100
					124	100
	16	SPAN	GPS + IMU	7.5	126	100
					127	100
	18	SPAN	GPS + IMU	7.5	505	100
	19	SPAN	GPS + IMU	5	228	100
					229	100
	20	SPAN	GPS + IMU	5	504	100
	21	SPAN	GPS + IMU	5	218	100
NC17-2 (INT)	1	SPAN	GPS + IMU	5	208	100
					307	100
	2	SPAN	GPS + IMU	5	203	100
					204	100
					225	100
					230	100
	3	SPAN	GPS + IMU	5	141	100
					501	100
	4	SPAN	GPS + IMU	5	502	100
					503	100
	5	SPAN	GPS + IMU	7.5	227	100
					328	100

Table 13: Gravity Processing Results

Survey	Flight Num.	Line Num.	Time of Deleted Data	Comments
No data was deleted in ES10				

Table 14: Bias from EGM08 by Line

Survey	Flight Num.	Line	EGM08 mean
NC17-1 (INT)	1	101	3.11
		102	2.19
	2	139	2.51
		140	1.76
	3	104	-0.02
	4	105	2.81
		106	1.76
	5	137	2.69
		138	2.31
	6	135	3.84
		136	2.4
	7	108	1.54
	8	109	2.46
		110	0.95
	9	133	3.34
		134	0.7
	10	111	3.13
		112	1.17
	11	113	2.39
		114	1.21
	12	131	5.06
		132	1.34
	13	115	2.1
		116	2.84
	14	117	2.53
		119	0.9
		120	0.97
	15	121	1.18
		122	1.57
		123	2.61
		124	3.42
	16	126	2.74
		127	3.99
	18	505	3.56
	19	228	0.37
		229	2.47
	20	504	1.86
	21	218	1.75

NC17-2 (INT)	1	208	3.16
		307	2.42
	2	203	2.56
		204	1.75
		225	2.72
		230	-0.05
	3	141	1.99
		501	1.33
	4	502	1.26
		503	0.91
	5	227	3.21
		328	2.19

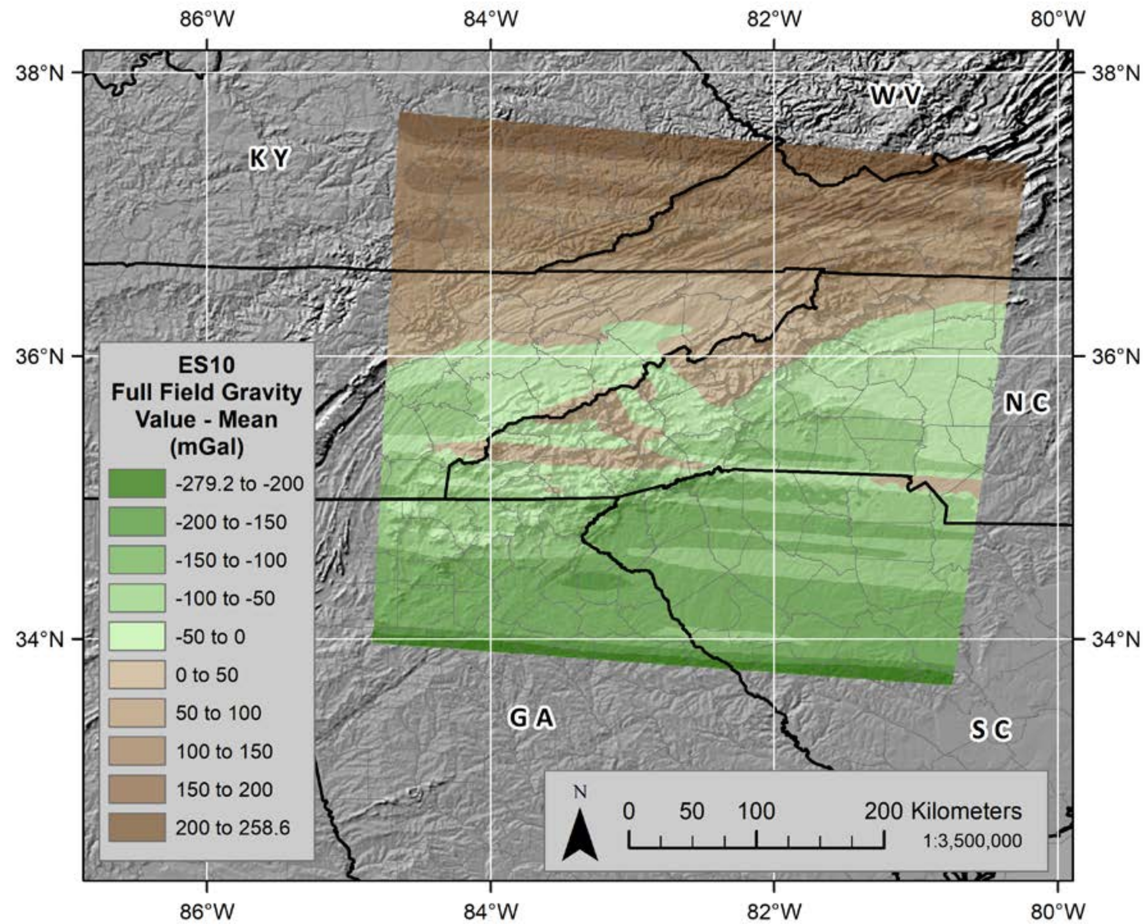

Figure 4: Full-field gravity at altitude (mean removed) for Block ES10. This is the data in the gravity release ".txt" file and includes the effects of differing altitudes along flight lines.

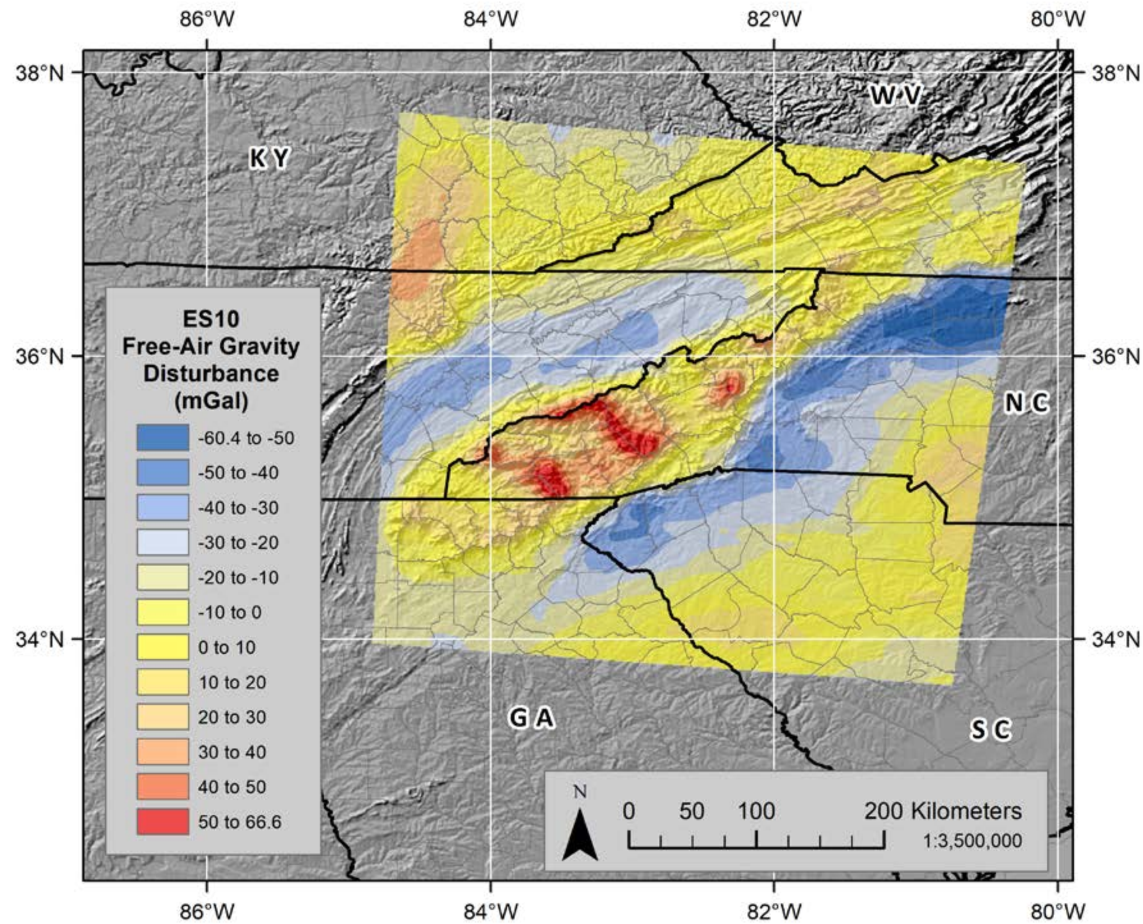

Figure 5: Free-air gravity disturbance for Block ES10 with respect to the GRS80 ellipsoid

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 ES10 data file, reference the webpage:
GRAV-D Science Team (2018). "Gravity for the Redefinition of the American Vertical Datum (GRAV-D) Project, Airborne Gravity Data; Block ES10". Available *DATE*. Online at: http://www.ngs.noaa.gov/GRAV-D/data_ES10.shtml

To reference the block and survey details, reference the block user manual:
GRAV-D Science Team (2018). "Block ES10 (Eastern South 10); 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_ES10.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."