NOAA Technical Memorandum NOS NGS 91

Absolute Gravity Measurement
University of Nebraska, Lincoln

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National Geodetic Survey
Silver Spring, MD
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Absolute Gravity Measurement, University of Nebraska, Lincoln

Instrument operation, data reduction, and reporting by Jeff Kanney

Work completed July 2022, report date: October 04, 2022

NOAA – National Geodetic Survey

GRAVITY STATION DESCRIPTION	STATION TYPE	STATION DESIGNATION
	Absolute Station	Museum
COUNTRY	STATE/PROVINCE - COUNTY	CITY
United States	Nebraska - Lancaster	Lincoln
LATITUDE	LONGITUDE	ELEVATION
40° 49' 12.5" N	96° 42' 7.1" W	357 meters
GRAVITY STATION MARK	AGENCY	INSCRIPTION
5 cm Brass Marker	NOAA-NGS	Museum
POSITION/ELEVATION REFERENCE	POSITION/ELEVATION SOURCE	SOURCE DESCRIPTION
WGS84	NOAA/NGS	CG6 Onboard GPS
POSITION/ELEVATION REMARKS	GRAVITY VALUE/SOURCE/DATE	
Estimated 3.5m uncertainty	g = 980178.079 ± 0.010 mGals (NOAA-NGS, July 2022)	

GRAVITY STATION DESCRIPTION	STATION TYPE	STATION DESIGNATION
	Absolute Station	Bell Tower
COUNTRY	STATE/PROVINCE - COUNTY	CITY
United States	Nebraska - Lancaster	Lincoln
LATITUDE	LONGITUDE	ELEVATION
40° 49' 12.8" N	96° 42' 9.3" W	358 meters
GRAVITY STATION MARK	AGENCY	INSCRIPTION
5 cm Brass Marker	NOAA-NGS	Bell Tower
POSITION/ELEVATION REFERENCE	POSITION/ELEVATION SOURCE	SOURCE DESCRIPTION
WGS84	NOAA/NGS	CG6 Onboard GPS
POSITION/ELEVATION REMARKS	GRAVITY VALUE/SOURCE/DATE	
Estimated 3.5m uncertainty	g = 980177.781 ± 0.010 mGals (NOAA-NGS, July 2022)	

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Introduction

The U.S. National Geodetic Survey (NGS) is tasked with the establishment and continued maintenance of the National Spatial Reference System (NSRS), which is the set of reference frames that all civilian federal government entities use to define any point of space within the United States and its territories. The vertical component of these coordinates (elevation) at any point is dependent on the value of the local gravity field [1]. To improve our knowledge of this component, NGS has acquired equipment to measure the absolute value of gravity with two instruments: The Micro-G LaCoste FG5 and A10 absolute gravimeters. The FG5 gravimeter is the current state-of-the-art laboratory instrument for measuring the strength of the local gravity field to roughly two parts in 1 billion (or ±2 μGal, see below). The A10 instrument operates on similar technology but has the advantages of being highly portable, operable from a 12-volt vehicle source, and achieves its accuracy in a much shorter measurement time than the FG5, although with a slightly lower accuracy (eight parts per billion). The absolute gravity value from any measurement can be easily transferred to another location through a relative gravity survey conducted with a Scintrex CG6 gravimeter. The relative gravity transfer typically only adds about ±1-2 μGal additional uncertainly while greatly expanding the ability to measure gravity at a location without having to physically occupy the site with the absolute gravimeter.

Background and Nomenclature

Gravity Units

The acceleration of a falling mass due to the Earth's gravity field at its surface, g, is typically measured in (the c-g-s) units of Gals (after Galileo):

$$1\ \text{Gal} \equiv 1\ \text{cm/s}^2$$
$$g \approx 980\ \text{Gal}$$
$$1\ \mu\text{Gal} \approx 1\text{x}10^{-9}g$$
$$1\ \mu\text{Gal} = 10\ \text{nm/s}^2$$

The current accuracy limit for state of the art A10 gravity meters is on the order of 8 μGal.

Survey: Instruments and Methods

The University of Lincoln gravity survey consisted of three separate tasks: absolute gravity measurements, vertical gravity gradient measurements, and finally, relative gravity transfer measurements.

Absolute Gravity Measurements

NGS owns and operates A10 s/n 025, manufactured by Micro-g LaCoste. The instrument operates by placing a retroreflector into freefall in a vacuum chamber, and its position is tracked with a frequency stabilized laser. The number of zero crossings in the interference signal is used to determine distance, and the time of the zero-crossings is recorded with a calibrated rubidium clock (nominal frequency 10 MHz). Proprietary software included with the gravimeter applies a least-squares fit of the data to the equations of motion [2]. This is used to determine the free parameter, g. Corrections are made for earth tides, ocean load, polar motion, and barometric pressure, and an independently determined vertical gravity gradient (see below). Occupation times are typically around 20 minutes depending on the magnitude of background noise observed during the measurement. To minimize measurement noise, a rigid shelter is set up around the instrument to block the wind and sun. In a typical 20-minute measurement, six sets of 120 drops per set are collected to reach the instrument accuracy in quiet conditions. To guard against instrument setup errors, the A10 is broken down, rotated about 90 degrees to force the instrument to re-level, and the measurement is repeated. If the repeat value lies within the manufacturer's stated repeatability range (two overlapping 10 µGal error bars, or 20 µGal), the measurement is concluded. These measurements were conducted on July 28, 2022.

Note that gravity was actually determined at the instrument height of approximately 72.2 cm that varied slightly between each setup. As described below, the vertical gravity gradient was measured separately and used to reduce the gravity value to the desired height.

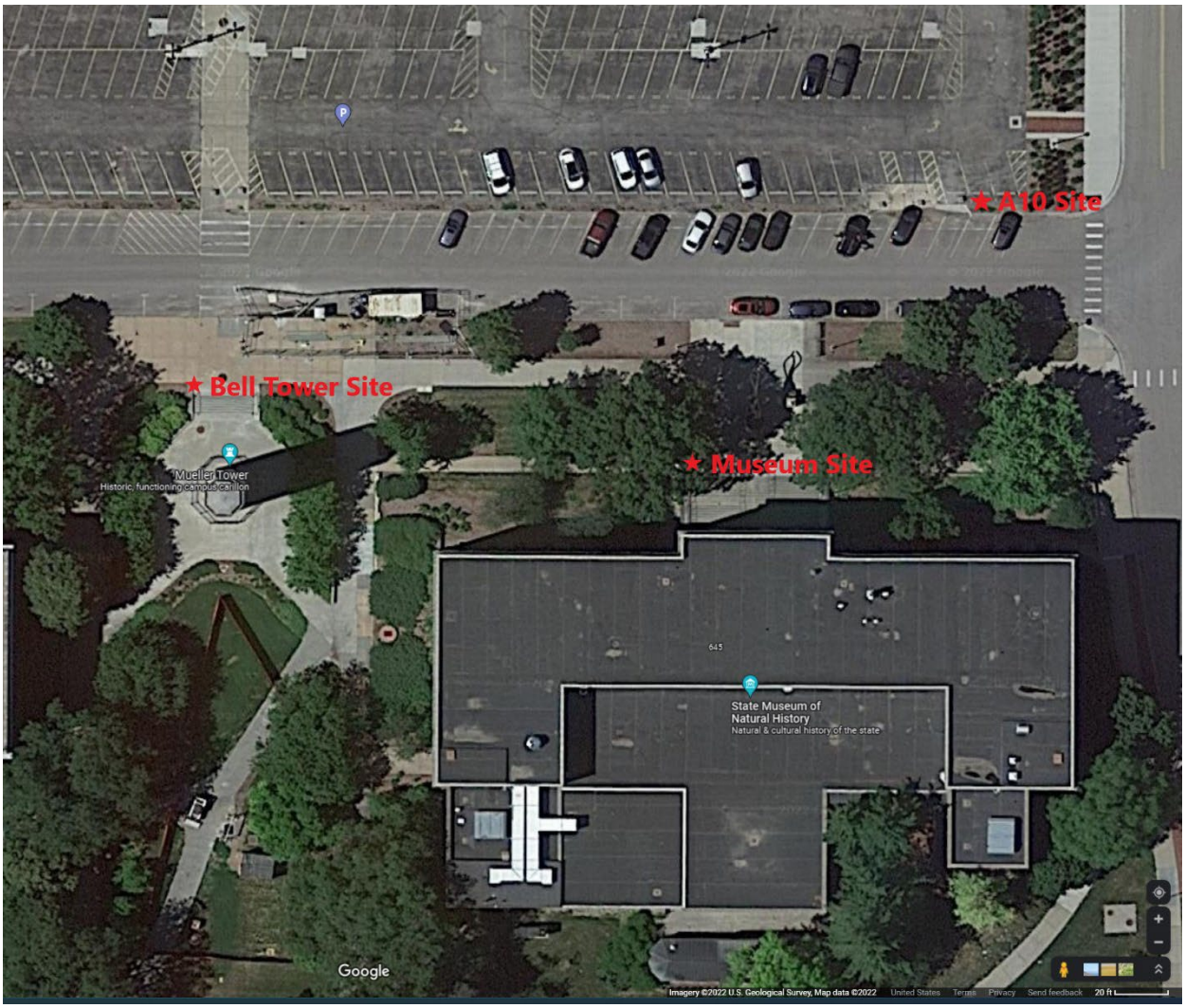

Figure 1. A10, Museum, and Bell Tower site location map.

Figures 2 (a) and (b). A10 site looking East and Northeast with blue wind shelter and gradient tripod depicted.

Relative Gravity Gradient Measurement

As one moves away from the center of the Earth, the acceleration due to gravity decreases in accordance with Newton's law. If the Earth were a perfect sphere, gravity would decrease at a nominal rate of 3.086 μGal/cm (near the surface). On the actual surface however, this value can fluctuate substantially: from <2 μGal/cm in a valley to >4 μGal/cm on a mountain top.

At the A10 measurement site, the vertical gravity gradient was measured using the Scintrex CG6 s/n 169. This is a small, spring-based relative gravity meter with a precision of a few μGal. The relative difference in gravity was measured between three fixed height tiers on a rigid tripod with heights set to about 25, 75, and 125 cm. After two three-minute occupations are completed at each tripod height, the data were analyzed on site with Apogee, a Matlab based relative gravity reduction software package developed by NGS. Apogee reads the 1Hz CG6 recorded data and uses a least squares method to determine a linear drift and relative gravity values for each tripod height, fitting for both linear and quadratic vertical gravity gradient values. The linear gradient value is then entered into the absolute gravity measurement software and the measurements are reprocessed to obtain the final gravity values at 72.2 cm. Next, the vertical gravity gradient is used to transfer the gravity value up to 75.0 cm, the second tier of the gradient tripod used as the starting point for the relative gravity transfer.

Relative Gravity Transfer

To transfer the absolute gravity value from the A10 measurement site to the markers installed at the Museum and Bell Tower sites, a relative gravity survey was conducted. To minimize transfer errors due to uncertainties in the vertical gravity gradient, the relative survey started from the second tier of the gradient tripod set up at the A10 site. Since the transfer from the A10 measurement height of 72.2 cm to the tripod height of 75 cm is very small, the transfer error induced from this procedure is kept extremely small. A three-minute CG6 measurement at 75cm above the ground at the A10 site was recorded onto a Windows tablet using the manufacturer's proprietary software that applies corrections for tides, ocean loading, and an approximate instrument drift in real time.

The CG6 was then relocated to the sites of interest, in this case the Museum and Bell Tower sites, and set up on the stock CG6 tripod with a fixed sensor height of 22.5 cm. A three-minute measurement was performed at each site. The entire process was repeated, and the data were again analyzed using Apogee. The measurements at every location repeated to ≤ 5 μGal (the manufacturer's stated instrument precision), and the measurement was concluded.

Figures 3 (a) and (b). Museum site looking south and east with the CG6 on the stock tripod.

Figures 4 (a) and (b). Bell Tower site looking south and close up

Data Reduction and Results

Absolute Gravity Results

A10 measurement 1: 980178207 ± 8 µGal at 72.2 cm
A10 measurement 2: 980178202 ± 8 µGal at 72.2 cm

Average gravity value: 980178205 ± 8 µGal at 72.2 cm

Vertical Gravity Gradient Results

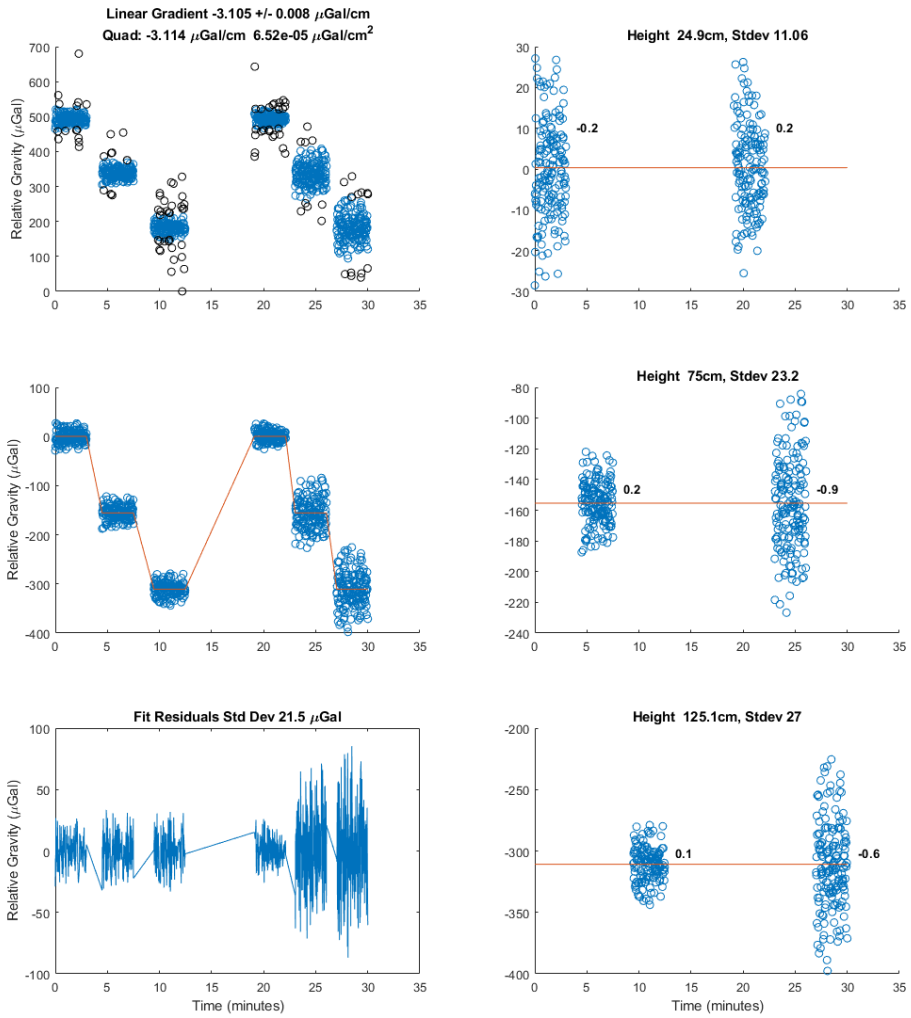

Figure 5. Vertical gravity gradient results at the A10 measurement site from Apogee. Top Left: all raw data with 3σ rejected outliers in black. Middle Left: drift corrected data with outliers removed. Bottom Left: all station residuals. Right: individual station (heights) residuals with individual occupation deltas posted in µGal next to each occupation. Since the final relative gravity values are calculated in a weighted least squares method, the occupation differences will not always sum to zero.

Relative Gravity Survey Results

A10 site at 75.0 cm: 0 ± 1µGal
Museum: -116.8 ± 1.1 µGal
Bell tower: -414.5 1.1 µGal

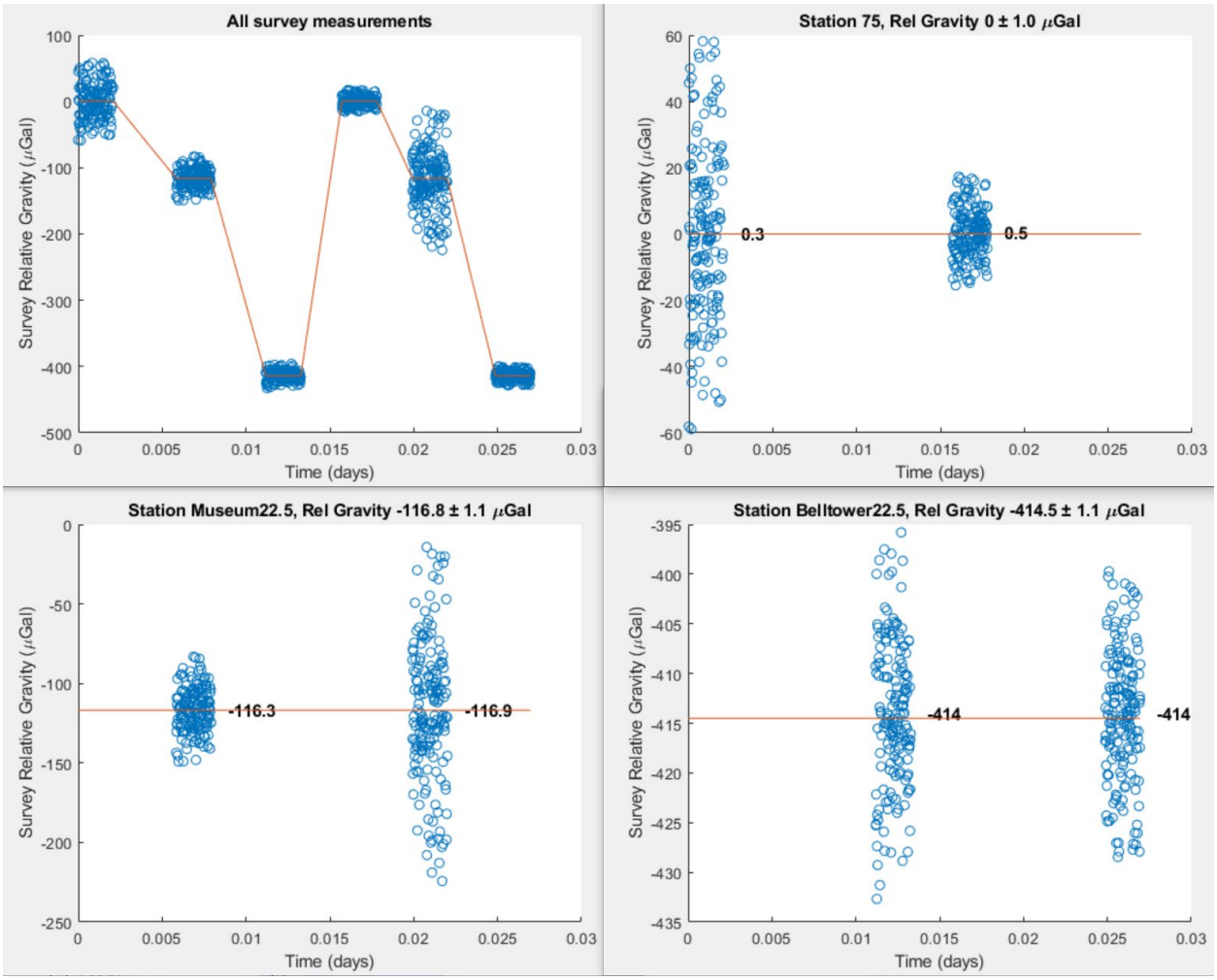

Figure 6. Relative gravity survey results. Top Left: All survey data with 3σ rejected outliers removed. Top Right, Lower Left, and Lower Right: Individual station residuals with final relative gravity difference in each title and individual occupation deltas in µGal next to each occupation. The final values will differ slightly from the occupation postings due to the weighted least squares network adjustment.

Final Gravity Value Derivation

Average gravity value:	980178205 ± 8 µGal at 72.2 cm A10 site
Transfer to 75.0 cm:	-8.7 ± 0.022 µGal (negligible uncertainty, not propagated)
Gravity at 75.0 cm at A10 site:	980178196 ± 8 µGal
Transfer to Museum at 22.5 cm:	-116.8 ± 2.1 µGal (add to A10 site value)
Gravity at Museum at 22.5 cm:	**980178079 ± 10 µGal**
Transfer to Bell Tower at 22.5 cm:	-414.5 2.1 µGal (add to A10 site value)
Gravity at Bell Tower at 22.5 cm:	**980177781 ± 10 µGal**

The uncertainty contribution of the vertical transfer at the A10 site was 2.8 cm x 0.008 µGal/cm = 0.022 µGal, which is insignificant and was ignored. For the relative gravity survey, since the gravity was propagated from the A10 site, the total uncertainty included the final uncertainty of the relative measurement at the A10 site plus the final uncertainty of the station measurement.

Instrument Verification

The Scintrex CG6 relative gravimeter s/n 169 was calibrated on July 19, 2022 using the Lefthand Canyon gravity calibration line established and maintained by NGS in order to generate a new calibration factor to be applied for all relative gravity measurements. The A10 gravimeter was run on pier AI in the gravity laboratory at the Table Mountain Geophysical Observatory for comparison to the FG5 value to verify proper instrument operation both before and after the mission.

A10 measurement 1 July 26, 2022:	979622742 µGal
A10 measurement 2 Aug 25, 2022:	979622740 µGal

FG5 value at pier AI:	979622745 µGal

References

1. Bernard Hoffmann-Wellenhof, Helmut Moritz, “Physical geodesy” second edition (2006): 64-172.
2. “Micro-g LaCoste’s g Absolute Gravity Processing Software,” last modified September 30, 2014, http://www.microglacoste.com/g.php .

Appendix A – A10 Processing Output Files

A10 report for measurement 1

Micro-g LaCoste g Processing Report
File Created: 08/31/22, 14:17:08

Project Name: UNLincoln Parking Lot 20220728a
g Acquisition Version: 4.041600
g Processing Version: 9.120423

Company/Institution: NGS
Operator: Jeff Kanney

Station Data
Name: UNLincoln
Site Code: 3
Lat: 40.82044 Long: -96.70153 Elev: 357.00 m
Setup Height: 0.00 cm
Transfer Height: 72.20 cm
Actual Height: 72.20 cm
Gradient: -3.105 µGal/cm
Nominal Air Pressure: 971.09 mBar
Barometric Admittance Factor: 0.30
Polar Motion Coord: 0.2430 " 0.3242 "
Earth Tide (ETGTAB) Selected
Potential Filename: C:\gData\gWavefiles\ETCPOT.dat
Delta Factor Filename: C:\gData\OceanLoad-UNLincoln.dff
Delta Factors

Start	Stop	Amplitude	Phase	Term
0.000000	0.000001	1.000000	0.0000	DC
0.000002	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\OceanLoad-UNLincoln.olf

Waves:	M2	S2	K1	O1	N2	P1	K2	Q1	Mf	Mm	Ssa

Amplitude (µGal): 0.692 0.305 0.859 0.516 0.092 0.260 0.078 0.106 0.000 0.000 0.000
Phase (deg): 61.3 359.3 51.5 63.7 78.3 52.5 349.2 72.9 0.0 0.0 0.0

Instrument Data
Meter Type: A10
Meter S/N: 025
Factory Height: 72.20 cm
Rubidium Frequency: 10000000.00763 Hz
Offset: 0.000 µGal
Laser: L-Series (025)
Blue Lock: 632.99022970 nm
Red Lock: 632.99130810 nm

Processing Results
Date: 07/29/22
Time: 14:00:46
DOY: 210
Year: 2022
Time Offset (D h:m:s): 0 0:0:0
Gravity: 980178207.05 µGal
Set Scatter: 3.95 µGal
Measurement Precision: 1.61 µGal
Total Uncertainty: 7.62 µGal
Red/Blue Separation: 9.03 µGal
Number of Sets Collected: 6
Number of Sets Processed: 6
Set #s Processed: 1,2,3,4,5,6
Number of Sets NOT Processed: 0
Set #s NOT Processed:
Number of Drops/Set: 120
Total Drops Accepted: 716
Total Drops Rejected: 4
Total Fringes Acquired: 750
Fringe Start: 19
Processed Fringes: 687
GuideCard Multiplex: 4
GuideCard Scale Factor: 25

Acquisition Settings
Sequence Interval: 6 min
Red/Blue Interval: 3 min
Drop Interval: 1 sec
Number of Sets: 8
Number of Drops: 120

Gravity Corrections
Earth Tide (ETGTAB): -42.62 µGal
Ocean Load: 1.04 µGal
Polar Motion: -5.56 µGal
Barometric Pressure: 1.96 µGal
Transfer Height: 0.00 µGal
Reference Xo: -0.00 µGal

Uncertainties
Sigma Reject: 3.00
Earth Tide Factor: 0.001
Average Earth Tide Uncertainty: 0.04 µGal
Ocean Load Factor: 0.10
Average Ocean Load Uncertainty: 0.10 µGal
Barometric: 1.00 µGal
Polar Motion: 0.05 µGal
Laser: 0.05 µGal
Clock: 0.50 µGal
System Type: 10.00 µGal
Tidal Swell: 0.00 µGal
Water Table: 0.00 µGal
Unmodeled: 0.00 µGal
System Setup: 3.00 µGal
Gradient: 0.000 µGal (0.018 µGal/cm)

Comments

A10 report for measurement 2

Micro-g LaCoste g Processing Report
File Created: 08/31/22, 14:18:04

Project Name: UNLincoln Parking Lot 20220728b
g Acquisition Version: 4.041600
g Processing Version: 9.120423

Company/Institution: NGS
Operator: Jeff Kanney

Station Data
Name: UNLincoln
Site Code: 3
Lat: 40.82044 Long: -96.70153 Elev: 357.00 m
Setup Height: 0.00 cm
Transfer Height: 72.20 cm
Actual Height: 72.20 cm
Gradient: -3.105 µGal/cm
Nominal Air Pressure: 971.09 mBar
Barometric Admittance Factor: 0.30
Polar Motion Coord: 0.2430 " 0.3242 "
Earth Tide (ETGTAB) Selected
Potential Filename: C:\gData\gWavefiles\ETCPOT.dat
Delta Factor Filename: C:\gData\OceanLoad-UNLincoln.dff
Delta Factors

Start	Stop	Amplitude	Phase	Term
0.000000	0.000001	1.000000	0.0000	DC
0.000002	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\OceanLoad-UNLincoln.olf

Waves:	M2	S2	K1	O1	N2	P1	K2	Q1	Mf	Mm	Ssa
Amplitude (µGal):	0.692	0.305	0.859	0.516	0.092	0.260	0.078	0.106	0.000	0.000	0.000

Phase (deg): 61.3 359.3 51.5 63.7 78.3 52.5 349.2 72.9 0.0 0.0 0.0

Instrument Data
Meter Type: A10
Meter S/N: 025
Factory Height: 72.20 cm
Rubidium Frequency: 10000000.00763 Hz
Offset: 0.000 µGal
Laser: L-Series (025)
Blue Lock: 632.99022970 nm
Red Lock: 632.99130810 nm

Processing Results
Date: 07/29/22
Time: 14:24:54
DOY: 210
Year: 2022
Time Offset (D h:m:s): 0 0:0:0
Gravity: 980178201.97 µGal
Set Scatter: 8.15 µGal
Measurement Precision: 3.33 µGal
Total Uncertainty: 8.02 µGal
Red/Blue Separation: 14.43 µGal
Number of Sets Collected: 6
Number of Sets Processed: 6
Set #s Processed: 1,2,3,4,5,6
Number of Sets NOT Processed: 0
Set #s NOT Processed:
Number of Drops/Set: 120
Total Drops Accepted: 715
Total Drops Rejected: 5
Total Fringes Acquired: 750
Fringe Start: 19
Processed Fringes: 687
GuideCard Multiplex: 4
GuideCard Scale Factor: 25

Acquisition Settings
Sequence Interval: 6 min
Red/Blue Interval: 3 min
Drop Interval: 1 sec
Number of Sets: 8
Number of Drops: 120

Gravity Corrections
Earth Tide (ETGTAB): -27.62 µGal
Ocean Load: 1.21 µGal
Polar Motion: -5.56 µGal
Barometric Pressure: 2.03 µGal
Transfer Height: 0.00 µGal
Reference Xo: -0.00 µGal

Uncertainties
Sigma Reject: 3.00
Earth Tide Factor: 0.001
Average Earth Tide Uncertainty: 0.03 µGal
Ocean Load Factor: 0.10
Average Ocean Load Uncertainty: 0.12 µGal
Barometric: 1.00 µGal
Polar Motion: 0.05 µGal
Laser: 0.05 µGal
Clock: 0.50 µGal
System Type: 10.00 µGal
Tidal Swell: 0.00 µGal
Water Table: 0.00 µGal
Unmodeled: 0.00 µGal
System Setup: 3.00 µGal
Gradient: 0.000 µGal (0.018 µGal/cm)

Comments