

Department of Natural Resources
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MARYLAND GEOLOGICAL SURVEY
Richard A. Ortt, Jr., Director

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LAND SUBSIDENCE MONITORING AT ARNOLD, BROAD CREEK, AND
CROFTON MEADOWS WELL FIELDS IN ANNE ARUNDEL COUNTY,
MARYLAND:

2016 SURVEY

by

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Prepared in cooperation with
Anne Arundel County Department of Public Works

2016

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ABBREVIATIONS USED IN THIS REPORT

ARNO-1	Arnold survey mark
BROA-1	Broad Creek survey mark
CORS	Continuously Operating Reference Stations
CROF-1	Crofton Meadows survey mark
GPS	global positioning system
NGS	National Geodetic Survey
OPUS	Online Positioning User Service

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KEY RESULTS

A GPS survey was completed May 3-13, 2016 to determine the heights of 3d marks at the Arnold, Broad Creek, and Crofton Meadows well fields in Anne Arundel County, Maryland. The GPS data were processed using the National Geodetic Survey's Online Positioning User Service (OPUS) Projects utility. The ellipsoid heights determined through OPUS Projects were 3.640 +/-0.001 m at Arnold, -6.175 +/-0.001 m at Broad Creek, and 7.101 +/-0.002 m at Crofton Meadows. Historical GPS data (1999 to 2015) for the same marks were re-processed using OPUS Projects. The range in ellipsoid height elevation over the period 1999 to 2016 was 0.047 m at Arnold, 0.028 m at Broad Creek, and 0.040 m at Crofton Meadows. There are no discernible trends in ellipsoid heights over the period of record to indicate land subsidence.

INTRODUCTION

Decades of groundwater withdrawals from unconsolidated, confined (artesian) coastal plain aquifers in Anne Arundel County, Maryland have resulted in significant drawdown of groundwater levels. Water levels have declined in some aquifers by as much as 130 ft from pre-pumping (Andreasen, 2007; Staley and others, in press). Projected increases in withdrawals to supply a growing population will result in additional drawdown (Andreasen, 2007). Withdrawing water from a confined aquifer reduces the hydrostatic pressure head in the pumped aquifer and in the adjacent confining layers (clay and silt). Reduction of hydrostatic pressure in the aquifer system resulting from the drawdown increases the load on the sediment which may lead to compaction and land subsidence. In the mid-Atlantic region, land subsidence ranging from 1.5 to 3.7 millimeters per year has occurred in the Franklin and Suffolk area of Virginia (lower Chesapeake Bay region) and is attributed to groundwater withdrawals from the Potomac Group aquifer system in Virginia (Patapsco and Patuxent aquifer systems in Maryland) (Davis, 1987; Eggleston and Pope, 2013). While not likely to cause major engineering problems, land subsidence related to groundwater withdrawals could exacerbate the problem of tidal flooding in low-lying areas caused by future sea-level rise. Permanent reduction in reservoir capacity by irreversible compaction of sediments may also occur.

HISTORICAL GPS DATA

Starting in 1994, GPS elevation measurements at 3d marks at Arnold, Broad Creek, and Crofton Meadows well fields have been made at approximately yearly intervals (fig. 1). GPS measurements from 1994 to 2015 were made by the Maryland State Highway Administration (Division of Plats and Surveys). Starting in 1995, three GPS occupations were made for each yearly observation period with each occupation lasting at least 5.5 hours. The 1994 survey used fewer and shorter sessions. Starting in 1998 all measurements were made using a dual frequency (L1/L2) GPS receiver.

The earlier GPS data were originally processed by Donald M. Mulcare (State Advisor to Maryland, National Geodetic Survey) and later by the Maryland State Highway Administration (Division

of Plats and Surveys). In 2016, the Maryland Geological Survey took over the function of both collecting and processing the GPS data. To maintain consistency in data processing and to take advantage of the most current National Geodetic Survey (NGS) Continuously Operating Reference Stations (CORS) information, the historical record was re-processed for the years with available raw GPS data (tab. 1). The data was processed using the NGS's OPUS Projects online utility to determine ellipsoid heights of the 3d marks. Ellipsoid heights were used as opposed to orthometric heights to avoid potential loss of accuracy associated with geoid models. OPUS Projects provides geodetic network solutions by baseline processing of simultaneous GPS observations. A detailed technical discussion of the concepts and processing used in OPUS Projects is provided in Armstrong (2015). Data-processing parameters specified in OPUS Projects used in this study included a piecewise linear tropospheric model with an interval of 7200 seconds, an elevation cutoff of 15.0 degrees and normal constraint weights. CORS stations used to process session network baselines and in network adjustment are shown in Table 2.

2016 GPS SURVEY

Two GPS occupations of the Arnold (ARNO-1), Broad Creek (BROA-1), and Crofton Meadows (CROF-1) 3d survey marks were conducted May 3-5 and May 10-13, 2016. The surveys were performed by staff of the Maryland Geological using the same dual frequency (L1/L2) GPS receiver (Topcon Hyper SR; serial number: 1064-11667 p/n:1000036-01) oriented north. The receiver was attached to a 2.0 m fixed-height SECU 5115 range pole with an 8-minute level vial. GPS readings were recorded at a 30-second sampling rate for 5.5 hours. The two occupations were offset by one hour to obtain different satellite geometry. Weather conditions on most days were cloudy and cool with occasional light rain.

The raw GPS data were processed using the OPUS Projects in the same manner used to process the historical data. The 2016 data were processed after 28 days from collection to obtain "precise" satellite ephemeridae (orbits).

Ellipsoid heights determined by OPUS Projects network adjustment at ARNO-1, BROA-1, and CROF-1 marks are given in Table 3. Reported ellipsoid accuracy ranges from 0.001 to 0.002 m.

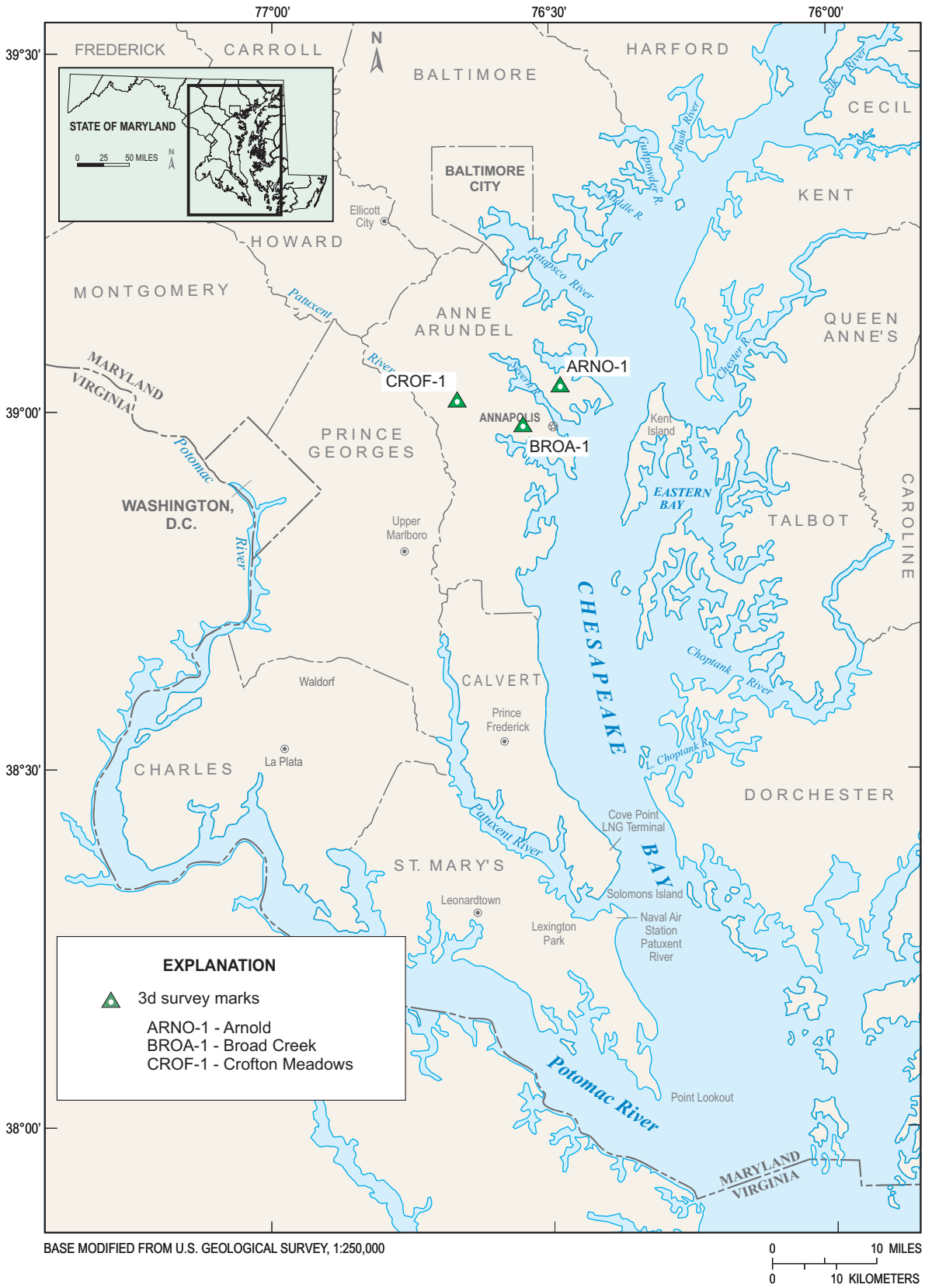


Figure 1. Location of GPS survey marks.

Table 1. Historical GPS data re-processed using OPUS Projects.

Year	Occupation date	Raw GPS data available?	GPS Receiver	GPS Antenna	Antenna height, m	Data re-processed?
1994	--	No	--		--	No
1995	5/16/1995 to 5/18/1995	No	Trimble 4000SST		--	No
1997	--	No	--			No
1998	6/2/1998 to 6/4/1998	Yes	Ashtech Z-12	Ashtech 70.01B	2.0	No. Recording interval not accepted by OPUS PROJECTS
1999	5/18/1999 to 5/20/1999	Yes	Ashtech Z-12	Ashtech 70.01B	2.0	Yes
2000	5/9/2000 to 5/11/2000	Yes	Ashtech Z-12	Ashtech 70.01B	2.0	Yes
2001	5/15/2001 to 5/17/2001	Yes	Ashtech Z-12	Ashtech 70.01B	2.0	Yes
2002	5/21/2002 to 5/23/2002	Yes	Ashtech Z-12	Ashtech 70.01B	2.0	Yes
2003	5/20/2003 to 5/22/2003	Yes	Ashtech Z-12	Ashtech 70.01B	2.0	Yes, except Broad Creek (data file was corrupted)
2004	5/25/2004 to 5/27/2004	No	Ashtech Z-12	Ashtech 70.01B	--	No
2005	--	No	--		--	No
2006	1/17/2006 to 1/19/2006 and 11/13/2006 to 11/15/2006	Yes	Thales Navigation Z-Max		1.8	Yes
2007	5/22/2007 to 5/24/2007	Yes	Thales Navigation Z-Max		1.8	Yes
2008	6/10/2008 to 6/12/2008	Yes	Thales Navigation Z-Max		1.8	Yes
2009	5/27/2009 to 5/29/2009	Yes	Thales Navigation Z-Max		1.8	Yes
2010	6/14/2010 to 6/16/2010	Yes	Thales Navigation Z-Max		1.8	Yes
2011	6/7/2011 to 6/9/2011	Yes	Thales Navigation Z-Max		1.8	No. Anomalous height results
2012	6/4/2012 to 6/6/2012	Yes	Thales Navigation Z-Max		2.0	Yes
2013	7/16/2013 to 7/18/2013	Yes	Thales Navigation Z-Max		1.8	Yes
2014	8/25/2014 to 8/28/2014	Yes	Topcon GR-5		1.8	Yes
2015	6/23/2015 to 6/25/2015	Yes	Topcon GR-5		1.8	Yes
2016	5/3/2016 to 5/13/2016	Yes	Topcon Hyper SR		2.0	Yes

Table 2. CORS sites used in processing GPS data.

[JPL, Jet Propulsion laboratory; NGS, National Geodetic Survey; USCG, U.S. Coast Guard; USNO, U.S. Naval Observatory]

CORS site	State	Dates active Year (nth day in year)	Owner	Use in OPUS Projects	
2002 - 2016					
GREENBELT (GODE)	MD	1997 (99) - present	JPL	Hub	Unconstrained
HORN POINT (HNPT)	MD	1999 (318) - present	NGS		Constrained
ANNAPOLIS 5 (ANP5)	MD	2007 (273) - present	USCG		Constrained
ALTERNATE MASTER (AMC2)	CO	2000 (242) - present	USNO	Troposphere correction	Unconstrained
1996 - 2001					
GREENBELT (GODE)	MD	1997 (99) - present	JPL	Hub	Unconstrained
HORN POINT (HNPT)	MD	1999 (318) - present	NGS		Constrained
GAITHERSBURG (GAIT)	MD	1994 (110) – 2009 (352)	NGS		Constrained
ALTERNATE MASTER (AMC2)	CO	2000 (242) - present	USNO	Troposphere correction	Unconstrained

Exceptions:

- 1999: USNA (U.S. Naval Academy) substituted as hub for GODE
- 2006 and 2007: ANP1 (USCG) substituted for ANP5
- 2008: MDSI (NGS) substituted for HNPT

Table 3. Summary of 2016 GPS survey.

Site	Date of occupation	Horizontal (IGS08 [2015.7825])		Vertical (IGS08 [2015.7825])		
		Latitude	Longitude	Ellipsoidal height (m)	Observations used, percent	Fixed ambiguities, percent
ARNO-1	5/3/16 and 5/10/16	N39 02 05.55513	W076 29 25.28037	3.640 +/- 0.001	98.9	98.6
BROA-1	5/4/16 and 5/11/16	N38 58 54.34516	W076 33 31.12462	-6.175 +/- 0.001	99.1	98.4
CROF-1	5/5/16 and 5/13/16	N39 01 01.59376	W076 40 28.51367	7.101 +/- 0.002	95.5	100

CHANGE IN ELLIPSOID HEIGHT OVER TIME

The change in ellipsoid height from the 1999 measurement at the 3d marks at Arnold, Broad Creek, and Crofton Meadows well fields are shown in Figure 2. Over the 17-year period, ellipsoid height varied from 0.047 m at Arnold, 0.028 m at Broad Creek, and 0.04 m at Crofton Meadows. The change in ellipsoid height is likely the result of inherent inaccuracies in the data collection and processing. There are no discernible trends in ellipsoid height over the period of record to indicate land subsidence.

REFERENCES

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- Armstrong, M.L.**, 2015, OPUS Projects, Online positioning user service baseline processing and adjustment software, User instructions and technical guide (ver. 2.5): National Geodetic Survey, NOAA, Silver Spring, Maryland, 116 p. [<http://www.ngs.noaa.gov/OPUS-Projects/OpusProjects.shtml>, accessed 7/20/2016]
- Davis, G.H.**, 1987, Land subsidence and sea level rise on the Atlantic Coastal Plain of the United States: Environ. Geol. Water Science, vol. 10, no.2, p. 67-80.
- Eggleston, Jack and Pope, Jason**, 2013, Land subsidence and relative sea-level rise in the southern Chesapeake Bay region: U.S. Geological Survey Circular 1392, 30 p.
- Staley, A.W., Andreasen, D.C., and Curtin, S.E.**, in press, Potentiometric surface and water-level difference maps of selected confined aquifers in Southern Maryland and Maryland's Eastern Shore, 1975-2015: Maryland Geological Survey Open-File Report 16-02-02, 30 p.

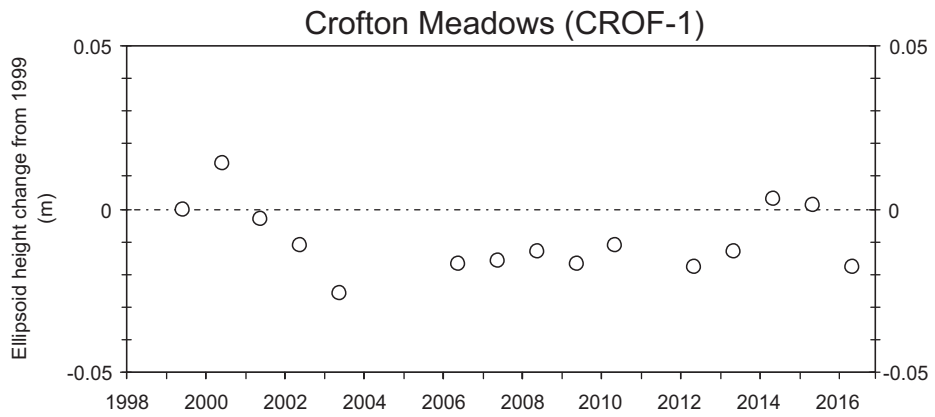
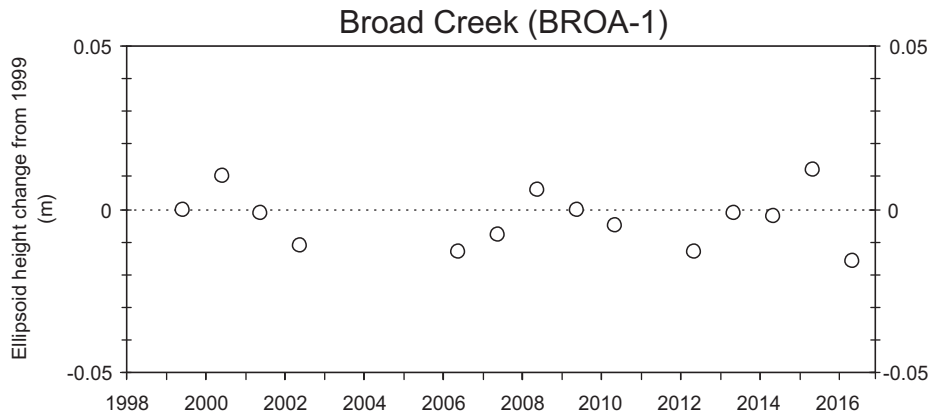
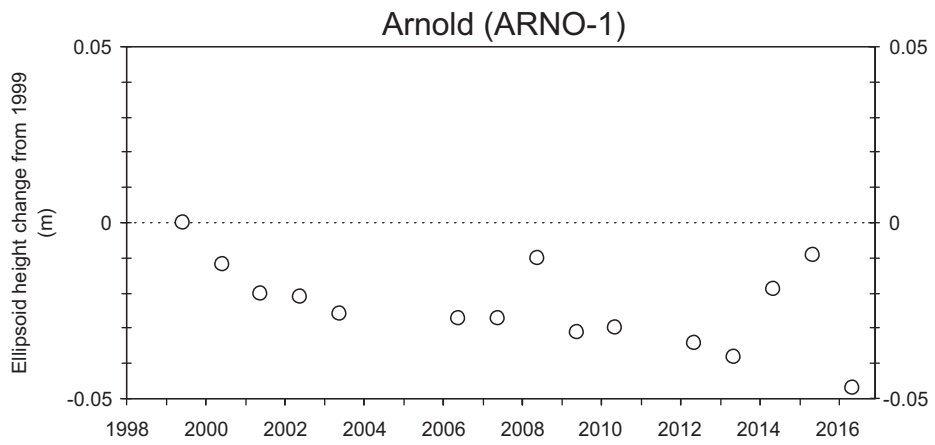


Figure 2. Change in ellipsoid height from 1999 at Arnold, Broad Creek and Crofton Meadows well fields.

Appendix A. OPUS Projects network adjustment for the 2016 GPS survey.

NGS OPUS-PROJECTS NETWORK ADJUSTMENT REPORT

```

=====
SOLUTION FILE NAME:          network-final.sum
SOLUTION SOFTWARE:          GPSCOM(1504.23)
SOLUTION DATE:              2016-06-06T12:37:15 UTC
STANDARD ERROR OF UNIT WEIGHT: 0.697
TOTAL NUMBER OF OBSERVATIONS: 334063
TOTAL NUMBER OF MARKS:      7
NUMBER OF CONSTRAINED MARKS: 2

START TIME:                  2016-05-03T00:00:00 GPS
STOP TIME:                    2016-05-13T23:59:30 GPS
FREQUENCY:                    L1 -> ION-FREE (L6)
OBSERVATION INTERVAL:        30 s
ELEVATION CUTOFF:            15 deg
TROPIC INTERVAL:              7200 s [PIECE-WISE LINEAR PARAMETERIZATION]
DD CORRELATIONS:              ON
  
```

INCLUDED SOLUTION	RMS	SOFTWARE	RUN DATE
1) 2016-124 A	1.0 cm	page5(1509.10)	2016-06-06T12:21 UTC
2) 2016-125 A	1.2 cm	page5(1509.10)	2016-06-06T12:26 UTC
3) 2016-126 A	1.2 cm	page5(1509.10)	2016-06-06T12:27 UTC
4) 2016-131 A	0.9 cm	page5(1509.10)	2016-06-06T12:35 UTC
5) 2016-132 A	1.0 cm	page5(1509.10)	2016-06-06T12:30 UTC
6) 2016-134 A	1.0 cm	page5(1509.10)	2016-06-06T12:31 UTC

BASELINE	LENGTH	RMS	OBS	OMITTED	FIXED IN SOLUTION(S)
gode-crof	13.195 km	1.3 cm	8201	4.7%	100.0% 3, 6
anp5-gode	18.887 km	1.4 cm	109449	2.4%	98.9% 1, 2, 3, ...
gode-broa	23.651 km	1.4 cm	8617	0.9%	98.4% 2, 5
gode-arno	29.173 km	1.4 cm	8504	1.2%	98.6% 1, 4
hnpt-gode	77.261 km	1.3 cm	111930	0.8%	98.7% 1, 2, 3, ...
amc2-gode	2379.465 km	1.3 cm	87362	0.2%	71.9% 1, 2, 3, ...

+++++
 UNCONSTRAINED MARKS
 +++++

MARK: amc2 (amc2 a 4)

REF FRAME:	NAD_83(2011) (2010.0000)	IGS08 (2016.3502)
X:	-1248595.493 m 0.000 m	-1248596.342 m 0.000 m
Y:	-4819429.539 m 0.001 m	-4819428.202 m 0.001 m
Z:	3976506.052 m 0.001 m	3976505.935 m 0.001 m
LAT:	38 48 11.22684 0.001 m	38 48 11.24584 0.001 m
E LON:	255 28 31.50420 0.000 m	255 28 31.45627 0.000 m
W LON:	104 31 28.49580 0.000 m	104 31 28.54373 0.000 m
EL HGT:	1912.295 m 0.001 m	1911.379 m 0.001 m
ORTHO HGT:	1930.825 m 0.025 m	(H = h - N WHERE N = GEOID12B HGT)

	UTM COORDINATES	STATE PLANE COORDINATES
	UTM (Zone 13)	SPC (0502 CO C)
NORTHING (Y)	4295036.134 m	412908.393 m
EASTING (X)	541281.210 m	999126.516 m
CONVERGENCE	0.29792300 deg	0.61518584 deg
POINT SCALE	0.99962098	0.99994935
COMBINED FACTOR	0.99932115	0.99964942

US NATIONAL GRID DESIGNATOR: 13SEC4128195036 (NAD 83)

+++++

MARK: **ARNO-1**

REF FRAME:	NAD_83(2011) (2010.0000)	IGS08 (2016.3476)
X:	1158910.191 m 0.000 m	1158909.340 m 0.000 m
Y:	-4823629.212 m 0.001 m	-4823627.762 m 0.001 m
Z:	3995327.616 m 0.001 m	3995327.554 m 0.001 m
LAT:	39 02 05.52384 0.001 m	39 02 05.55513 0.001 m
E LON:	283 30 34.73994 0.000 m	283 30 34.71963 0.000 m
W LON:	76 29 25.26006 0.000 m	76 29 25.28037 0.000 m
EL HGT:	4.929 m 0.001 m	3.640 m 0.001 m
ORTHO HGT:	38.178 m 0.016 m	(H = h - N WHERE N = GEOID12B HGT)

	UTM COORDINATES	STATE PLANE COORDINATES
	UTM (Zone 18)	SPC (1900 MD)
NORTHING (Y)	4321702.600 m	152000.068 m
EASTING (X)	371008.301 m	444125.196 m
CONVERGENCE	-0.93874162 deg	0.31987373 deg
POINT SCALE	0.99980488	0.99995369
COMBINED FACTOR	0.99980411	0.99995292

US NATIONAL GRID DESIGNATOR: 18SUJ7100821702 (NAD 83)

MARK: **BROA-1**

REF FRAME:	NAD_83(2011) (2010.0000)		IGS08 (2016.3504)	
X:	1154021.102 m	0.000 m	1154020.251 m	0.000 m
Y:	-4828609.429 m	0.001 m	-4828607.978 m	0.001 m
Z:	3990739.560 m	0.001 m	3990739.497 m	0.001 m
LAT:	38 58 54.31392	0.001 m	38 58 54.34516	0.001 m
E LON:	283 26 28.89575	0.000 m	283 26 28.87538	0.000 m
W LON:	76 33 31.10425	0.000 m	76 33 31.12462	0.000 m
EL HGT:	-4.885 m	0.001 m	-6.175 m	0.001 m
ORTHO HGT:	28.282 m	0.016 m	(H = h - N WHERE N = GEOID12B HGT)	

	UTM COORDINATES	STATE PLANE COORDINATES
	UTM (Zone 18)	SPC (1900 MD)
NORTHING (Y)	4315907.104 m	146073.150 m
EASTING (X)	364996.455 m	438241.240 m
CONVERGENCE	-0.98064615 deg	0.27701256 deg
POINT SCALE	0.99982443	0.99995155
COMBINED FACTOR	0.99982520	0.99995232

US NATIONAL GRID DESIGNATOR: 18SUJ6499615907 (NAD 83)

+++++

MARK: **CROF-1**

REF FRAME:	NAD_83(2011) (2010.0000)		IGS08 (2016.3539)	
X:	1143680.987 m	0.001 m	1143680.136 m	0.001 m
Y:	-4828541.842 m	0.001 m	-4828540.392 m	0.001 m
Z:	3993797.495 m	0.001 m	3993797.432 m	0.001 m
LAT:	39 01 01.56253	0.001 m	39 01 01.59376	0.001 m
E LON:	283 19 31.50685	0.000 m	283 19 31.48633	0.000 m
W LON:	76 40 28.49315	0.000 m	76 40 28.51367	0.000 m
EL HGT:	8.389 m	0.002 m	7.101 m	0.002 m
ORTHO HGT:	41.199 m	0.016 m	(H = h - N WHERE N = GEOID12B HGT)	

	UTM COORDINATES	STATE PLANE COORDINATES
	UTM (Zone 18)	SPC (1900 MD)
NORTHING (Y)	4320008.238 m	149954.794 m
EASTING (X)	355025.641 m	428181.666 m
CONVERGENCE	-1.05442006 deg	0.20424380 deg
POINT SCALE	0.99985880	0.99995288
COMBINED FACTOR	0.99985748	0.99995156

US NATIONAL GRID DESIGNATOR: 18SUJ5502520008 (NAD 83)

MARK: gode (gode a 2)

REF FRAME:	NAD_83(2011) (2010.0000)		IGS08 (2016.3502)
X:	1130774.432 m	0.000 m	1130773.581 m 0.000 m
Y:	-4831255.027 m	0.001 m	-4831253.573 m 0.001 m
Z:	3994200.519 m	0.001 m	3994200.452 m 0.001 m
LAT:	39 01 18.18964	0.001 m	39 01 18.22081 0.001 m
E LON:	283 10 23.42543	0.000 m	283 10 23.40476 0.000 m
W LON:	76 49 36.57457	0.000 m	76 49 36.59524 0.000 m
EL HGT:	15.786 m	0.001 m	14.493 m 0.001 m
ORTHO HGT:	48.166 m	0.016 m	(H = h - N WHERE N = GEOID12B HGT)

	UTM COORDINATES	STATE PLANE COORDINATES
	UTM (Zone 18)	SPC (1900 MD)
NORTHING (Y)	4320774.468 m	150431.505 m
EASTING (X)	341854.670 m	414996.118 m
CONVERGENCE	-1.15043529 deg	0.10868974 deg
POINT SCALE	0.99990796	0.99995308
COMBINED FACTOR	0.99990548	0.99995060

US NATIONAL GRID DESIGNATOR: 18SUJ4185420774 (NAD 83)

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CONSTRAINED MARKS

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MARK: anp5 (anp5 a 2)

CONSTRAIN: 3d NORMAL

ADJUST X:	0.002m (0.000m)	Y:	0.003m (0.001m)	Z:	-0.003m (0.001m)
ADJUST N:	-0.001m (0.001m)	E:	0.003m (0.000m)	H:	-0.004m (0.001m)

REF FRAME:	NAD_83(2011) (2010.0000)		IGS08 (2016.3502)
X:	1149299.244 m	0.000 m	1149298.391 m 0.000 m
Y:	-4827708.344 m	0.001 m	-4827706.886 m 0.001 m
Z:	3993217.434 m	0.001 m	3993217.362 m 0.001 m
LAT:	39 00 37.00433	0.001 m	39 00 37.03552 0.001 m
E LON:	283 23 26.71974	0.000 m	283 23 26.69930 0.000 m
W LON:	76 36 33.28026	0.000 m	76 36 33.30070 0.000 m
EL HGT:	21.691 m	0.001 m	20.390 m 0.001 m
ORTHO HGT:	54.688 m	0.016 m	(H = h - N WHERE N = GEOID12B HGT)

	UTM COORDINATES	STATE PLANE COORDINATES
	UTM (Zone 18)	SPC (1900 MD)
NORTHING (Y)	4319149.078 m	149219.713 m
EASTING (X)	360669.014 m	433843.136 m
CONVERGENCE	-1.01311755 deg	0.24525148 deg
POINT SCALE	0.99983904	0.99995259
COMBINED FACTOR	0.99983564	0.99994919

US NATIONAL GRID DESIGNATOR: 18SUJ6066919149 (NAD 83)

MARK: hnpt (hnpt a 4)
 CONSTRAIN: 3d NORMAL
 ADJUST X: -0.000m (0.000m) Y: -0.006m (0.001m) Z: 0.004m (0.001m)
 ADJUST N: -0.000m (0.001m) E: -0.002m (0.000m) H: 0.007m (0.001m)

REF FRAME: NAD_83(2011) (2010.0000) IGS08 (2016.3502)
 X: 1196627.026 m 0.000 m 1196626.178 m 0.000 m
 Y: -4846359.964 m 0.001 m -4846358.495 m 0.001 m
 Z: 3956723.212 m 0.001 m 3956723.138 m 0.001 m
 LAT: 38 35 19.71004 0.001 m 38 35 19.74112 0.001 m
 E LON: 283 52 10.66804 0.000 m 283 52 10.64858 0.000 m
 W LON: 76 07 49.33196 0.000 m 76 07 49.35142 0.000 m
 EL HGT: -26.667 m 0.001 m -27.987 m 0.001 m
 ORTHO HGT: 8.229 m 0.016 m (H = h - N WHERE N = GEOID12B HGT)

	UTM COORDINATES	STATE PLANE COORDINATES
	UTM (Zone 18)	SPC (1900 MD)
NORTHING (Y)	4271753.563 m	102722.194 m
EASTING (X)	401553.852 m	475762.994 m
CONVERGENCE	-0.70509878 deg	0.54580948 deg
POINT SCALE	0.99971935	0.99996232
COMBINED FACTOR	0.99972353	0.99996650

US NATIONAL GRID DESIGNATOR: 18SVH0155371753 (NAD 83)