The effects of forest canopy structural change on carbon uptake and storage

Mapping Project Report
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1. LiDAR System Description and Specifications

This survey was performed with an Optech GEMINI Airborne Laser Terrain Mapper (ALTM) serial number 06SEN195 mounted in a twin-engine Cessna Skymaster (Tail Number N337P). The instrument specifications are listed in table 1.

Operating Altitude	150 - 4000 m, Nominal
Horizontal Accuracy	1/5,500 x altitude (m AGL); 1 sigma
Elevation Accuracy	5 - 30 cm; 1 sigma
Range Capture	Up to 4 range measurements, including 1st, 2nd, 3rd, last returns
Intensity Capture	12-bit dynamic range for all recorded returns, including last returns
Scan FOV	0 - 50 degrees; Programmable in increments of ±1degree
Scan Frequency	0 – 70 Hz
Scanner Product	Up to Scan angle x Scan frequency = 1000
Roll Compensation	±5 degrees at full FOV – more under reduced FOV
Pulse Rate Frequency	33 - 167 kHz
Position Orientation System	Applanix POS/AV 510 OEM includes embedded BD950 12-channel 10Hz GPS receiver
Laser Wavelength/Class	1047 nanometers / Class IV (FDA 21 CFR)
Beam Divergence nominal (full angle)	Dual Divergence 0.25 mrad (1/e) or 0.80 mrad (1/e)

Table 1 – Optech GEMINI specifications.

See http://www.optech.ca for more information from the manufacturer.

2. Description of PI's Areas of Interest.

The survey area is an irregular polygon enclosing a portion of the University of Michigan Biological Station (UMBS) located at the northern tip of the Lower Peninsula of Michigan, on the southwest shore of Douglas Lake, just off Riggsville Road / Robinson Road/C-64. The survey polygon is approximately 40 square kilometers in size. A map image of the polygon is shown below in Figure 1 (Google Earth). The polygon at its widest region in the east west direction is 8.27 km, and 6.27 km at its longest North to South direction region.

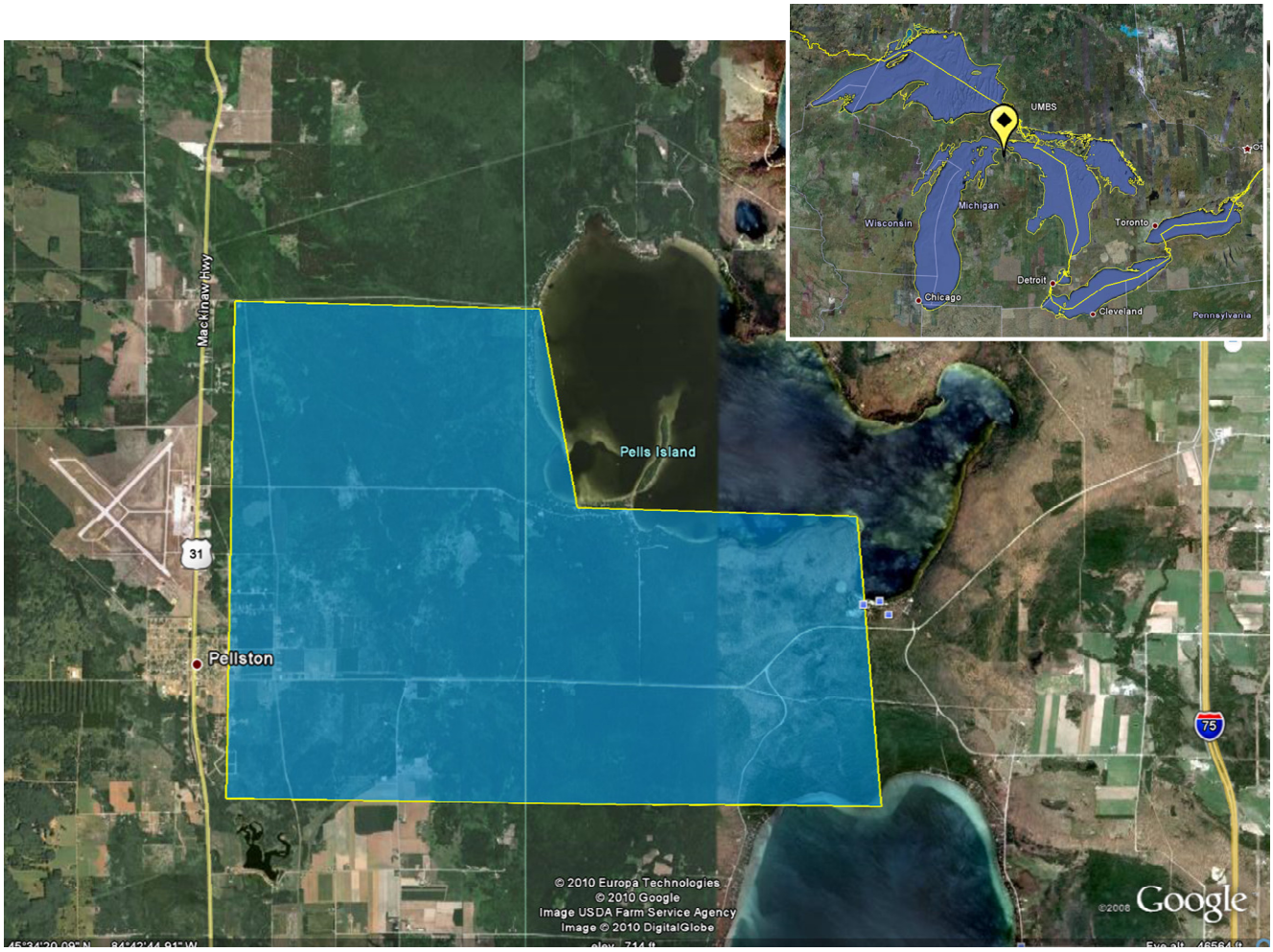

Figure 1 – Shape and location of survey polygon (Google Earth).

3. Airborne Survey Planning Process.

The survey planning was performed considering nominal values of 600m for flight altitude above the terrain, a mean flying speed of 60 m/s and a swath overlap of 50%. Taken into account these values and the layout of the area of interest the optimized flight plan consisted of 35 flight lines in the east-west direction. The main objective of this project was to map the canopy structure. Because of this it was decided to perform the survey with a Laser pulse repetition frequency of 125 kHz. Scan frequency (mirror oscillation rate) was held to 40 Hz and the scan angle (Field-of-View or FOV) was limited to +/- 20 degrees. These parameters yield a scan product (frequency x angle) of 800 out of a system maximum of 1000, or about 80% of system limits. The combination of all these parameters should nominally yield a point density of 9.5 points per m². Figure 2 show screen captures from the planning software displaying the planned flight lines along with other survey parameters; these are also summarized in table 2.

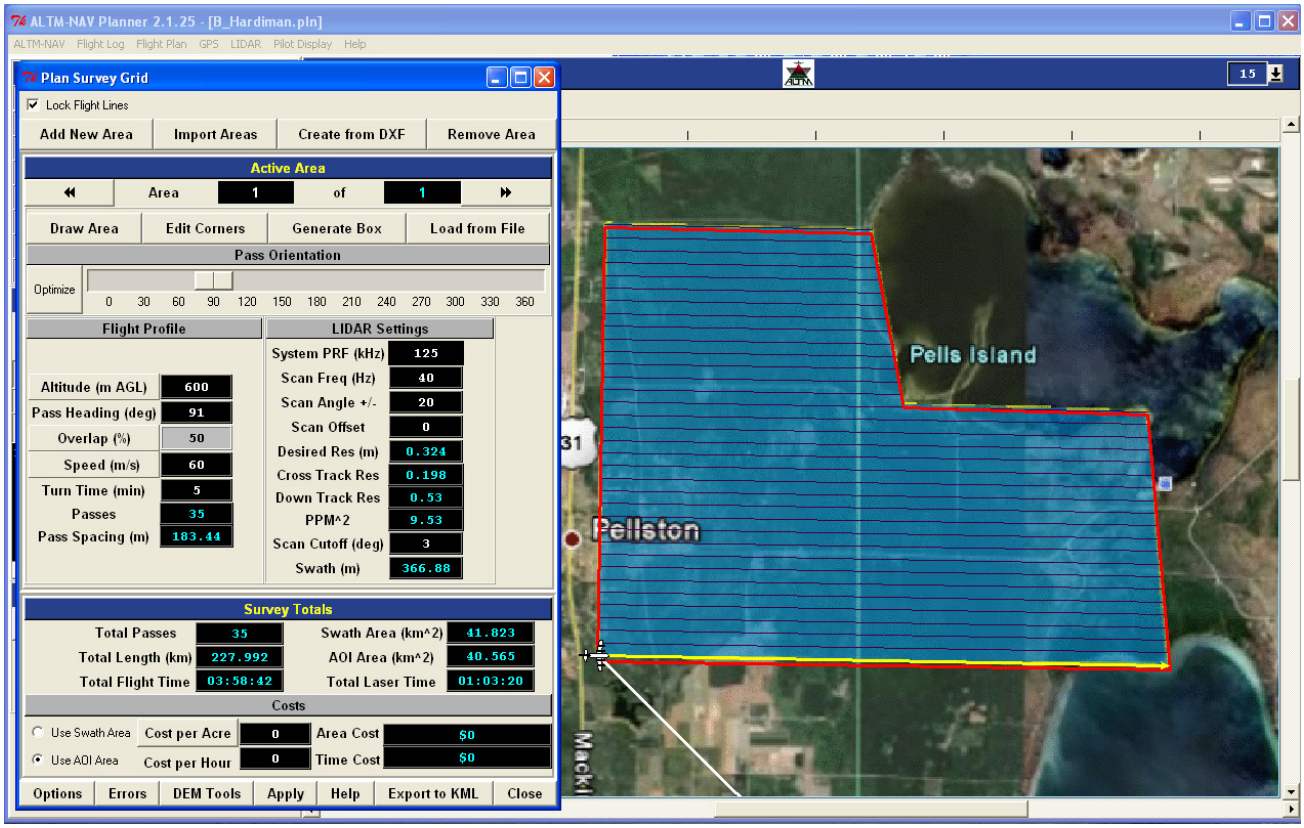

Figure 2. North-South flight lines from the planning software.

Nominal Flight Parameters		Equipment Settings		Survey Totals	
Flight Altitude	600 m	Laser PRF	125 kHz	Total Passes	35
Flight Speed	60 m/s	Beam Divergence	0.25 mrad	Total Length	227.9 km
Swath Width	366.88 m	Scan Frequency	40 Hz	Total Flight Time	3.9783 hrs
Swath Overlap	50%	Scan Angle	± 20°	Total Laser Time	1.0555 hrs
Point Density	9.53 p/m²	Scan Cutoff	3°	Total Swath Area	41.823 km^2
		Scan Offset	0	Total AOI Area	40.565 km^2

Table 2 – Survey totals. Area of Interest is abbreviated AOI.

4. LiDAR and GPS Data Collection Campaign.

This survey was flown on August 28, 2009 in a single flight consisting 41 mapping strips, four f which were for calibration data proposes. The total flight time was over 3.5 hours, with a total Laser On Time of 1.7381 Hours. Data were collected following the instrument parameters prescribed by the original mission planning as described in the previous section. For the project 740,250,000 Laser shots were fired yielding 768,900,000 measurements, which represent an average 9 per square meter of the survey polygon.

Two GPS reference station locations were used during the survey; labeled KPEL and MISI. KPEL was a temporary station set by NCALM on the grounds of the Pellston Regional Airport during the survey. MISI is a NGS Continuously Operating Reference Station (CORS) located at St. Ignace, MI and operated by the Michigan DOT (http://www.ngs.noaa.gov/cgi-cors/corsage.prl?site=MISI). The distance between KPEL and the center of the polygon was roughly 4 km and from MISI was roughly 33 km. All reference GPS observations were logged at 1 Hz. Ground equipment at KPEL consisted of ASHTECH (Thales Navigation) Z-Extreme receiver, with choke ring antenna (Part# 700936.D) mounted on 1.3-meter fixed-height tripod. The airborne receiver is an integrated GPS receiver module Trimble BD950, logging at 10 Hz. Figure 3 shows the location of the stations and the survey polygon.

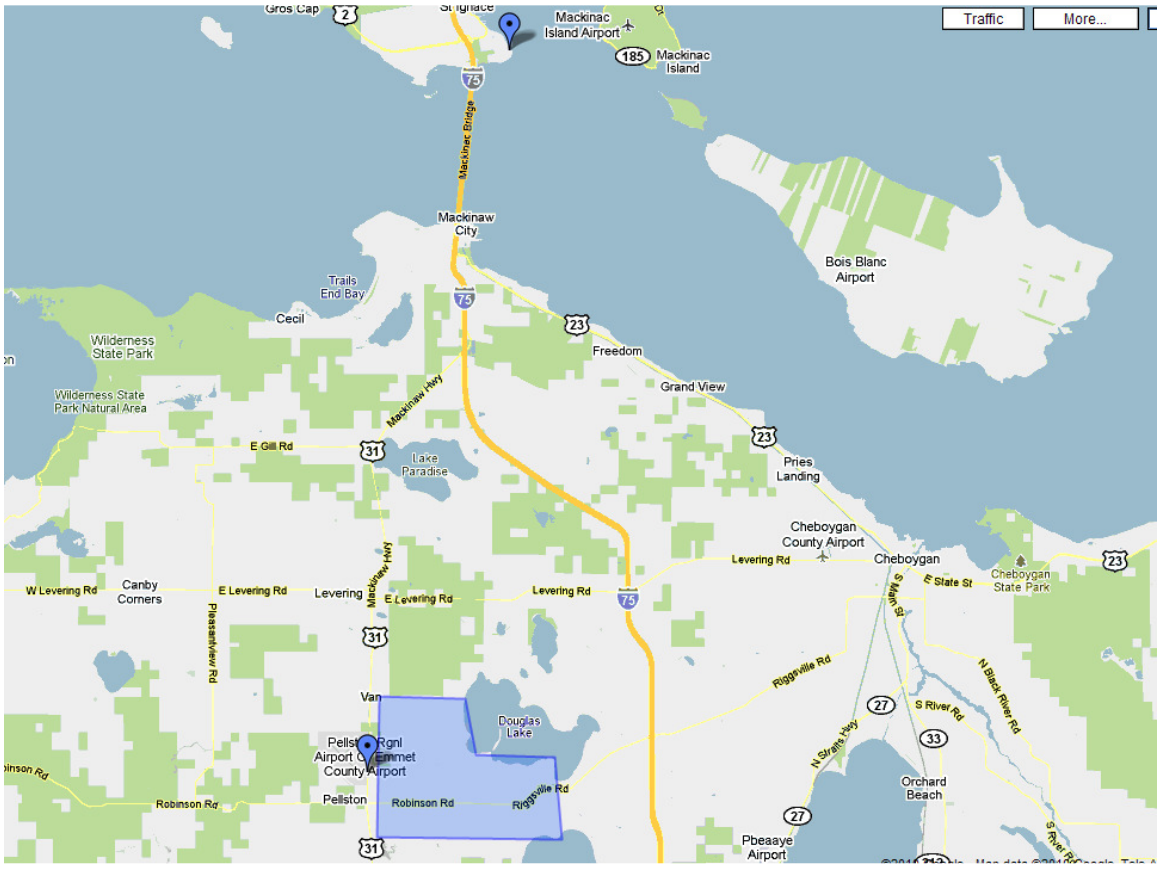

Figure 3. GPS stations and survey polygon location.

5. Data Processing and Final Product Generation.

5.1. GPS & INS Navigation Solution.

Reference coordinates for the KPEL station are derived from a single observation session taken over the project duration and submitted to the NGS on-line processor OPUS which processes static differential baselines tied to the international CORS network. MISI is a CORS station so its published coordinates were used in the processing. For further information on OPUS see http://www.ngs.noaa.gov/OPUS/ and for more information on the CORS network see http://www.ngs.noaa.gov/CORS/ .

Airplane trajectories for this survey were processed using KARS (Kinematic and Rapid Static) software by Dr. Gerald Mader of the NGS Research Laboratory. KARS kinematic GPS processing uses the dual-frequency phase history files of the reference and airborne receivers to determine a high-accuracy fixed integer ionosphere-free differential solution at 1 Hz. Trajectories are obtained per reference station and then the trajectories are differenced with one another. The standard deviation of the difference components for these two separate solutions (1 from KPEL, 1 from MISI) are 0.005, 0.011 and 0.038 meters for the East, North and Up component respectively. The final selected trajectory was derived from the KPEL station observations.

After GPS processing, the trajectory solution and the raw inertial measurement unit (IMU) data collected during the flights are combined in APPLANIX software POSPac MMS (Mobile Mapping Suite Version 5.2). POSPac MMS implements a Kalman Filter algorithm to produce a final, smoothed, and complete navigation solution including both aircraft position and orientation at 200 Hz. This final navigation solution is known as an SBET (Smoothed Best Estimated Trajectory).

5.2. Strip Point Cloud Generation

An SBET together with laser ranges and mirror angles are finally combined in Optech's DashMap software (Version 5.2) to generate a flight-strip point cloud in LAS format. All point cloud coordinates were processed with respect to **NAD83** and referenced to the international CORS network. The projection is UTM Zone 16N, with units in meters**. Heights are NAVD88** orthometric heights computed using the **NGS GEOID 03.** Scan angle cut-offs are done to improve the overall DEM accuracy as points farthest from the scan nadir are the most affected by small errors in pitch, roll and scanner mirror angle measurements. Moreover, scan angle cut-offs are done to eliminate points at the edge of the scan lines for improving the overall DEM accuracy as the points farthest from the scan nadir are the most affected by small errors in pitch, roll and scanner mirror angle measurements. A scan cutoff angle of 3 degrees was used.

5.3. Calibration, Matching, Validation, and Accuracy Assessment

Relative calibration is done for each flight by the following method:

1. Planning and flying swaths with 50% side lap.
2. Surveying crossing flight-lines over calibration areas and over the project polygon.
3. Analyzing these overlaps and cross-lines in TerraMatch software. (see http://www.terrasolid.fi/en/products/4).

TerraMatch employs a least-squares approach (minimizing the height differences between computed laser surfaces from individual crossing and/or overlapping flight lines) to calculate the best-fit values for four parameters: three bore sight angle alignments (roll, pitch, and yaw), and the scanner mirror-angle scale factor.

TerraMatch was run to a convergent solution on every flight line. Values for height disagreements between individual flight line surfaces ranged from a high of 10 cm to a low of 3 cm. Individual swath height disagreements averaged approximately 7.0 cm. The values obtained for different lines were then averaged to get the correction for roll, pitch and yaw values and the final configuration file is created to be used for outputting files in DashMap.

Ground check points (1023 in file car240.utm) were produced by driving a vehicle with a roof-mounted GPS antenna and receiver over a gravel road that fronted the Pellston airport. This road was then surveyed with the ALTM using the same survey parameters as were used on the project survey. A comparison of these check points with their nearest neighbor LiDAR shot returned an average difference of 0.05 M with a standard deviation of 0.065 M.

5.4 Classification and Filtering

TerraSolid's TerraScan (http://terrasolid.fi) software was used to classify the LIDAR points and generate the "bare-earth" dataset.

The classification used for this project consists of two algorithms:

1) Removal of isolated points. This routine removes points that have no close neighbors (within 5 meters).

2) Ground Classification. This routine classifies ground points by iteratively building a triangulated surface model. The algorithm starts by selecting some local low points assumed as sure hits on the ground, within a specified windows size. This makes the algorithm particularly sensitive to low outliers in the initial dataset, hence the requirement of removing as many erroneous low points as possible in the first step.

   The routine builds an initial model from selected low points. Triangles in this initial model are mostly below the ground with only the vertices touching ground. The routine then starts molding the model upwards by iteratively adding new laser points to it. Each added point makes the model follow ground surface more closely. Iteration parameters determine how close

a point must be to a triangle plane so that the point can be accepted to the model. Iteration angle is the maximum angle between point, its projection on triangle plane and closest triangle vertex. The smaller the Iteration angle, the less eager the routine is to follow changes in the point cloud. Iteration distance parameter makes sure that the iteration does not make big jumps upwards when triangles are large. This helps to keep low buildings out of the model. The routine can also help avoid adding unnecessary points to the ground model by reducing the eagerness to add new points to ground inside a triangle with all edges shorter than a specified length.

Ground classification parameters used:
Max Building Size (window size): 10.0 m
Max Terrain Angle: 88.0
Iteration Angle: 6.0
Iteration Distance: 1.2 m

6. Deliverables Description.

All deliverables were processed with respect to NAD83 (CORS96) reference frame. The projection is UTM zone 16N with units in meters. Heights are NAVD88 orthometric heights computed from GRS80 ellipsoid heights using NGS GEOID03 model.

Deliverables include the following:

1. Point Cloud in LAS format, classified as ground or non-ground, in 1 km tiles.
2. ESRI format 1-m DEM from all first-stop points.
3. ESRI format 1-m DEM from all ground classified points.

Deliverable 1 is the point cloud in LAS format, classified by automated routines in TerraScan (http://www.terrasolid.fi/en/products/terrascan) as ground or non-ground in tiles created from the combined flight strips. The tiles follow a naming convention using the lower left UTM coordinate (minimum X, Y) as the seed for the file name as follows: XXXXXX_YYYYYYY For example if the tile bounds coordinate values from easting equals 675000 through 676000, and northing equals 5047000 through 5048000 then the tile filename incorporates 675000_5047000

Deliverable 2 is the ESRI format DEM mosaic derived from deliverable 1 using default-class (first-stop) points at 1 meter node spacing. Elevation rasters are first created using Golden Software's Surfer 8 Kriging algorithm. The following parameters are used:

```
Gridding Algorithm: Kriging
Variogram: Linear
Nugget Variance: 0.15 m
MicroVariance: 0.00 m
SearchDataPerSector: 7
SearchMinData: 5
SearchMaxEmpty: 1
SearchRadius: 5m
```

The resulting Surfer grids are transformed into ArcInfo binary DEMs and hill shades using in-house Python and AML scripts.

Deliverable 3 is the ESRI format DEM mosaic derived from deliverable 1 using only ground-class points. The rasters are first created using Golden Software's Surfer 8 Kriging algorithm using the following parameters:

```
Gridding Algorithm: Kriging
Variogram: Linear
Nugget Variance: 0.15 m
MicroVariance: 0.00 m
SearchDataPerSector: 7
SearchMinData: 5
SearchMaxEmpty: 1
SearchRadius: 25m
```

The resulting Surfer grids are transformed into ArcInfo binary DEMs and hill shades using in-house Python and AML scripts.

7. Appendices

APPENDIX A – OPUS Solution for GPS Reference Stations

```
FILE: KPEL240z.09o 000055900

1008   NOTE:  Antenna offsets supplied by the user were zero.  Coordinates
1008   returned will be for the antenna reference point (ARP).
1008
                            NGS OPUS SOLUTION REPORT
                            ========================

All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: http://www.ngs.noaa.gov/OPUS/about.html#accuracy

     USER: jcfernan@ufl.edu                        DATE: February 05, 2010
RINEX FILE: kpel240m.09o                           TIME: 17:58:22 UTC


 SOFTWARE: page5  0909.08 master10.pl 081023      START: 2009/08/28  12:46:00
EPHEMERIS: igs15465.eph [precise]                  STOP: 2009/08/28  17:29:30
 NAV FILE: brdc2400.09n                       OBS USED: 11106 / 11576   :  96%
 ANT NAME: ASH700936D_M    NONE             # FIXED AMB:    57 /    58   :  98%
ARP HEIGHT: 0.0                             OVERALL RMS: 0.010(m)


REF FRAME: NAD_83(CORS96)(EPOCH:2002.0000)            ITRF00 (EPOCH:2009.6565)

        X:       406583.947(m)   0.015(m)            406583.191(m)   0.015(m)
        Y:     -4454685.544(m)   0.015(m)          -4454684.203(m)   0.015(m)
        Z:      4531557.686(m)   0.026(m)           4531557.623(m)   0.026(m)

      LAT:   45 33 49.30974      0.030(m)        45 33 49.34079      0.030(m)
    E LON:  275 12 53.99462      0.014(m)       275 12 53.96552      0.014(m)
    W LON:   84 47  6.00538      0.014(m)        84 47  6.03448      0.014(m)
   EL HGT:          181.006(m)   0.008(m)                179.978(m)   0.008(m)
ORTHO HGT:          216.255(m)   0.043(m) [NAVD88 (Computed using GEOID09)]

                       UTM COORDINATES    STATE PLANE COORDINATES
                        UTM (Zone 16)         SPC (2112 MI C)
Northing (Y) [meters]     5047959.416           249779.723
Easting (X)  [meters]      672854.725          5967341.728
Convergence  [degrees]     1.58196376          -0.29551482
Point Scale                0.99996736           0.99997133
Combined Factor            0.99993898           0.99994296

US NATIONAL GRID DESIGNATOR: 16TFR7285447959(NAD 83)



                            BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
DI1840 MISI ST. IGNACE CORS ARP            N455113.059 W0844210.851   32851.6
DJ7835 CHB6 CHEBOYGAN 6 CORS ARP           N453913.280 W0842757.016   26831.8
DJ8965 CHB5 CHEBOYGAN 5 CORS ARP           N453912.546 W0842756.300   26837.8

                NEAREST NGS PUBLISHED CONTROL POINT
QK0181      F 75                           N453410.    W0844710.        645.6

This position and the above vector components were computed without any
knowledge by the National Geodetic Survey regarding the equipment or

field operating procedures used.
```

APPENDIX B – CORS Data Sheet for MISI Reference Station

```
DATABASE =  ,PROGRAM = datasheet, VERSION = 7.80
1        National Geodetic Survey,   Retrieval Date = FEBRUARY  5, 2010
 DI1840 ***********************************************************************
 DI1840  CORS        -  This is a GPS Continuously Operating Reference Station.
 DI1840  DESIGNATION -  ST. IGNACE CORS ARP
 DI1840  CORS_ID     -  MISI
 DI1840  PID         -  DI1840
 DI1840  STATE/COUNTY-  MI/MACKINAC
 DI1840  USGS QUAD   -  ST IGNACE (1976)
 DI1840
 DI1840                        *CURRENT SURVEY CONTROL
 DI1840  ______________________________________________________________________
 DI1840* NAD 83(CORS)-  45 51 13.05935(N)    084 42 10.85171(W)     ADJUSTED
 DI1840* NAVD 88     -              **(meters)            **(feet)
 DI1840  ______________________________________________________________________
 DI1840  EPOCH DATE  -        2002.00
 DI1840  X           -     410,826.561 (meters)                      COMP
 DI1840  Y           -  -4,431,110.463 (meters)                      COMP
 DI1840  Z           -   4,554,039.841 (meters)                      COMP
 DI1840  ELLIP HEIGHT-         151.660 (meters)          (10/??/06) ADJUSTED
 DI1840  GEOID HEIGHT-         -35.42  (meters)                      GEOID09
 DI1840  HORZ ORDER  -  SPECIAL (CORS)
 DI1840  ELLP ORDER  -  SPECIAL (CORS)
 DI1840
 DI1840.ITRF positions are available for this station.
 DI1840.The coordinates were established by GPS observations
 DI1840.and adjusted by the National Geodetic Survey in October 2006.
 DI1840.The coordinates are valid at the epoch date displayed above.
 DI1840.The epoch date for horizontal control is a decimal equivalence
 DI1840.of Year/Month/Day.
 DI1840
 DI1840
 DI1840.The PID for the CORS L1 Phase Center is DI1841.
 DI1840
 DI1840.The XYZ, and position/ellipsoidal ht. are equivalent.
 DI1840
 DI1840.The ellipsoidal height was determined by GPS observations
 DI1840.and is referenced to NAD 83.
 DI1840
 DI1840.The geoid height was determined by GEOID09.
 DI1840
 DI1840;                     North         East     Units Scale Factor Converg.
 DI1840;SPC MI N     -   121,541.649 8,178,363.421   MT  0.99993105   +1 39 36.9
 DI1840;SPC MI N     -   398,758.69 26,831,900.99   iFT  0.99993105   +1 39 36.9
 DI1840
 DI1840!             -  Elev Factor  x  Scale Factor =   Combined Factor
 DI1840!SPC MI N     -   0.99997622  x   0.99993105  =   0.99990728
 DI1840
 DI1840                          SUPERSEDED SURVEY CONTROL
 DI1840
 DI1840.No superseded survey control is available for this station.
 DI1840
 DI1840_U.S. NATIONAL GRID SPATIAL ADDRESS: 16TFR7832780350(NAD 83)
 DI1840_MARKER: STATION IS THE ANTENNA REFERENCE POINT OF THE GPS ANTENNA
 DI1840
 DI1840                          STATION DESCRIPTION
 DI1840
 DI1840'DESCRIBED BY NATIONAL GEODETIC SURVEY 2006
 DI1840'STATION IS A GPS CORS.  LATEST INFORMATION INCLUDING POSITIONS AND
 DI1840'VELOCITIES ARE AVAILABLE IN THE COORDINATE AND LOG FILES ACCESSIBLE
 DI1840'BY ANONYMOUS FTP OR THE WORLDWIDE WEB.
 DI1840'   FTP CORS.NGS.NOAA.GOV: CORS/COORD  AND  CORS/STATION_LOG
 DI1840'   HTTP://WWW.NGS.NOAA.GOV  UNDER PRODUCTS AND SERVICES.
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