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Project Name: AIRBORNE LASER SWATH MAPPING: FLATHEAD LAKE BIOLOGICAL STATION, MONTANA, USA

Photograph of Harrison Lake Taken During the Survey

1. Survey Area

The project area consisted of a rectangular box with dimensions of 9 kilometers by 10 kilometers (90 square kilometers). Corner coordinates in NAD83 UTM Zone 12 for this rectangle are:

287000 5366000
287000 5376000
296000 5376000
296000 5366000

Two flights were needed to cover the project area. They were flown on May 29th and 30th, 2005. Figure 1 is an image showing the shape and location of the project area.

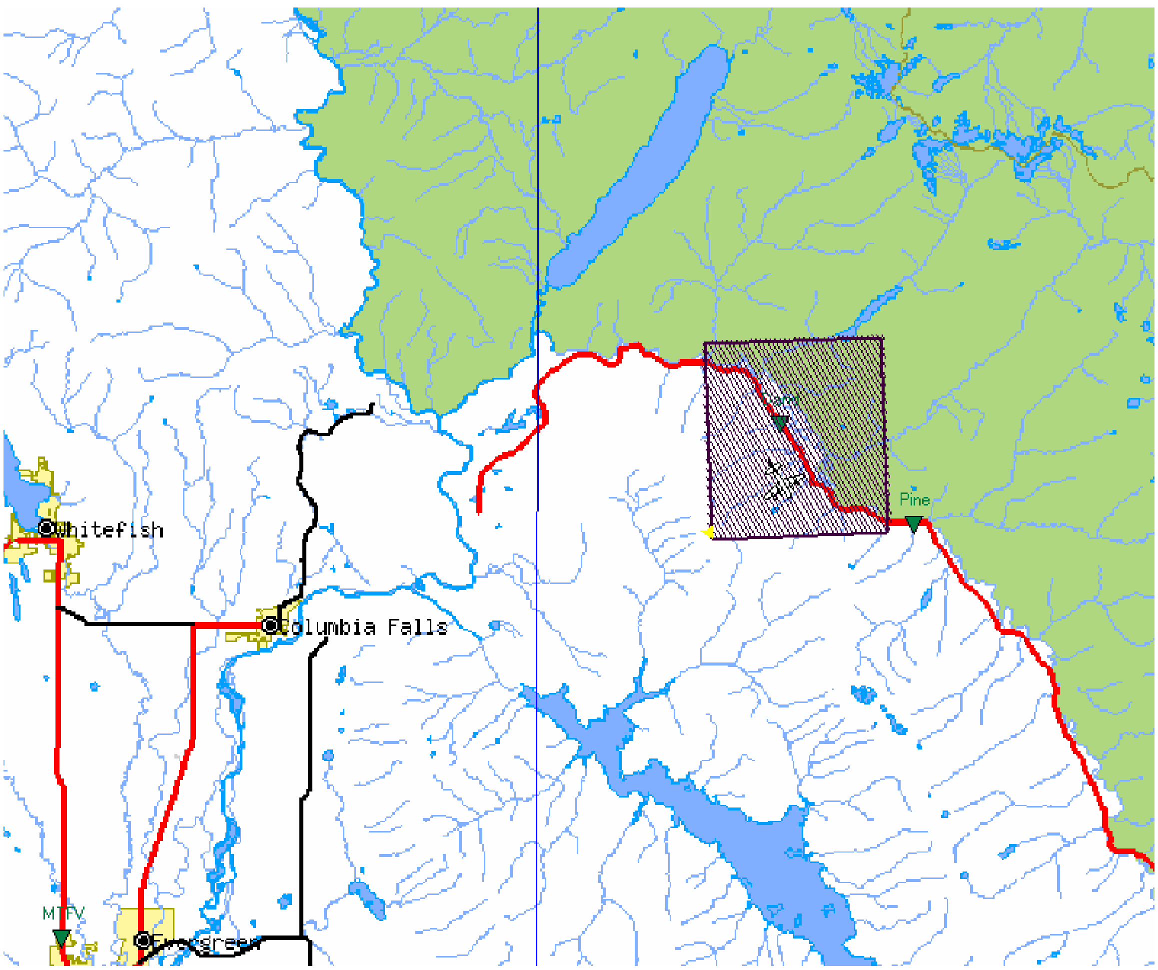


Figure 1 - Project location map (green triangles represent locations of GPS base stations).

2. Survey Parameters

Due to the relief of the area, change in elevation for each survey line was minimized by orienting the lines approximately Northwest-Southeast (actual planned heading of 330˚). Survey lines were numbered from 1 to 59 starting at the southwestern corner of the box. The lines were flown in the following manner: lines 1 through 26 were surveyed in order during the first flight, followed by two cross lines; lines 27-59 were surveyed in reverse order for the second flight, also followed by two cross lines. Flying height is typically targeted at 600m; however, due to the rapid changes in elevation, heights above ground level (AGL) sometimes exceeded 1200m and averaged about 800m. Flying speed was planned at 60m/s (117 nm/h). Planned point spacing per swath was approximately 1m along-track at nadir, 2.1m along-track at the scan edge, and 0.73m cross-track. Overlap coverage was targeted at approximately 100% (50% sidelap). Additional parameters are shown below in Table 1. Table 2 lists values at 800m AGL for comparison.

Flying Speed (m/s)	**Scan Spacing (m)**	**Pulse Rate (p/sec)**
60.0	**2.1**	**33333.0**
Indicated Air Speed (nm/h)	**Scan Width (m)**	**Pulses Per Scan**
116.6	**436.8**	**595.2**
Scan Rate (+/- degrees)	**Scan Angle (d)**	**Distance Between Range Points Along Scan (m)**
28.0	**20.0**	**0.73**
Flying Height (meters AGL)	**Flight line Spacing (m)**	**Swath Overlap (m)**
600	**219.8**	**260.0**

Table 1 - Survey Parameters at 600 meters AGL.

Flying Speed (m/s)	**Scan Spacing (m)**	**Pulse Rate (p/sec)**
60.0	**2.1**	**33333.0**
Indicated Air Speed (nm/h)	**Scan Width (m)**	**Pulses Per Scan**
116.6	**582.4**	**595.2**
Scan Rate (+/- degrees)	**Scan Angle (d)**	**Distance Between Range Points Along Scan (m)**
28.0	**20.0**	**0.98**
Flying Height (meters AGL)	**Flight line Spacing (m)**	**Swath Overlap (m)**
800	**219.8**	**363.0**

Table 2 - Survey Parameters at 800 meters AGL.

Laser-on	**2.68**	**Hours**
Air Time(Laser-off)	**5.07**	**Hours**
Total Flight Time	**7.75**	**Hours**

Table 3 - Laser–on time, air time, and total flight time.

3. GPS Reference Stations:

Two GPS reference station locations were used during the survey. The GPS receivers were placed on newly set marks PINE and DAND (marked as green triangles in Figure 1). DAND was observed for 4.5 hours during the first flight and 6.5 hours during the second flight. PINE was observed for 5 hours during the first flight and 6 hours during the second flight. GPS observations were logged at 1-second epochs and were submitted to the NGS online processor OPUS with solution files included as Appendix A. The repeat sessions on PINE and DAND both yielded a positional difference of about .03 meters. The final coordinates for these stations were computed using a weighted average of the OPUS solutions. For more on OPUS see http://www.ngs.noaa.gov/OPUS/ and for more information on the CORS network see http://www.ngs.noaa.gov/CORS/. Ground equipment consisted of ASHTECH (Thales Navigation) Z-Extreme receivers, with choke ring antennas (Part# 700936.D) mounted on 2-meter fixed-height tripods.

4. Navigation Processing

Airplane trajectories for this survey were processed using REALM processing software by Optech, Inc. The REALM solution is phase-differenced L1 only, without fixing phase ambiguities; these types of solutions (REALM) are generally less suitable over long baseline lengths (over 25 kilometers) but usually very good over short baseline separation distances, which is the case with this project. The REALM L1 trajectory was used for the processing of the final navigation solution because the KARS (Kinematic and Rapid Static) software dual-frequency phase-differenced fixed integer solution was incomplete due to a problem with the aircraft GPS antenna and/or cable, which has since been corrected. Figure 2 is a plot of the differences in Easting, Northing, and Height of two trajectories one being the L1 REALM trajectory processed using PINE, and the other being the L1 REALM trajectory processed using DAND. The standard deviation of the differences in the Easting position of these two trajectories is .004m, in Northing .009m, and in height .012m.

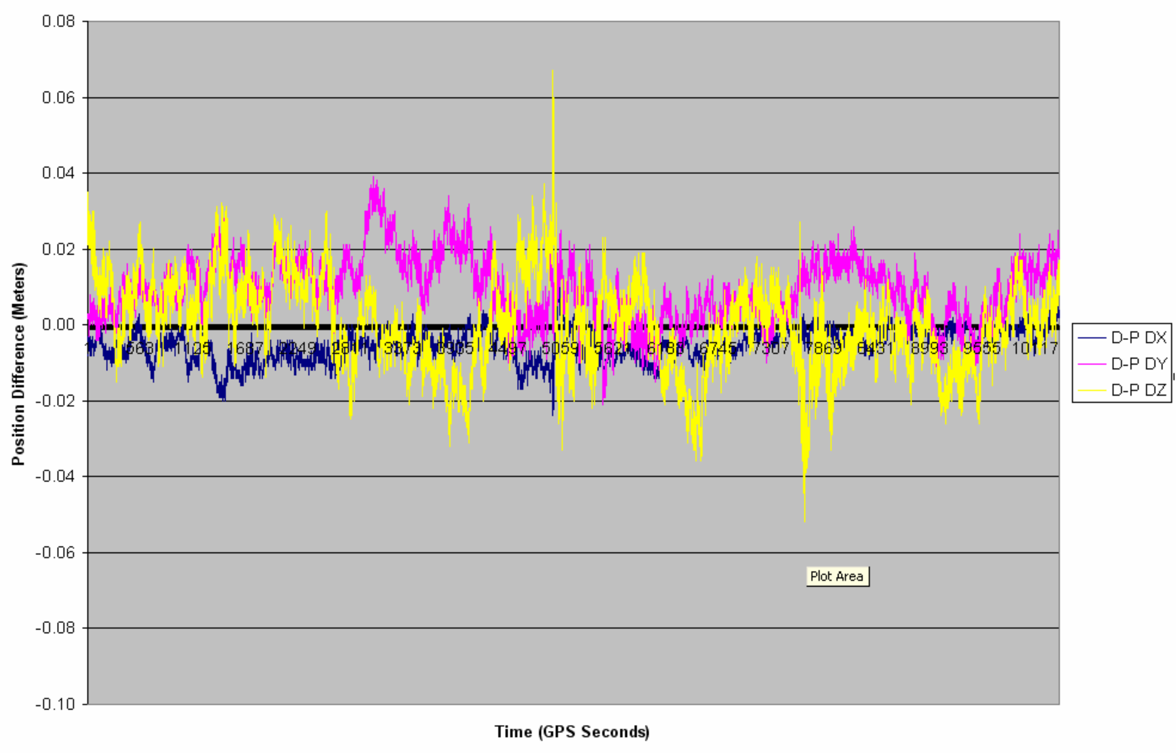


Figure 2 – Positional differences in trajectory positions

5. Laser Point Processing

All coordinates were processed with respect to NAD83 and referenced to the national CORS network. The projection is UTM Zone 12 with units in meters. Heights are NAVD88 orthometric heights computed using NGS GEOID03 model. The most complete output format is nine-column ASCII (space delimited), one file per flight strip. The nine columns are as follows: 1. GPS time (seconds of week); 2. Easting last stop; 3. Northing last stop; 4. Height last stop; 5. Intensity last stop; 6. Easting first stop; 7. Northing first stop; 8. Height first stop; 9. Intensity first stop.
Note that in these 9-column files no geoid model has been applied - height values are ellipsoid heights and these height values will NOT match orthometric heights (elevations) found in the 3-column output or in the 1-meter DEM grid nodes.

Note that the UTM zone code (12)is appended to the Easting coordinate in this nine-column format. The UF has utility software to reformat these files, for example to extract last stop elevations and intensities and remove the UTM zone code. These utilities are written in C /C++ programming language and are available for distribution.

During processing, a scan cutoff angle of 2 degrees was used to eliminate points at the edge of the scan lines. This was done to improve the overall DEM accuracy (points farthest from the scan nadir are the most affected by small errors in pitch, roll and scanner mirror angle measurements).

Points with very low intensity values were also filtered out (intensity values less than 7), because these points also tend to be the least accurate. This is due to the fact that very weak return pulses yield the noisiest range measurements. These points represent a very small percentage of the total number of points, usually in the neighborhood of a few hundredths of one percent.

All calibration files as well as all raw observation files (both GPS and ALTM) necessary to reprocess this project in its entirety are archived by UC Berkeley.

6. Ground Truth and Calibration

In order to provide on-site calibration and ground truth, a section of US-2 was surveyed using vehicle-mounted GPS, and then surveyed with the ALTM during the flight. Comparisons were made between the heights of the vehicle-collected GPS and the airborne laser scanner. This allowed for a check on the calibration of the airborne scanner as well as a measure of the accuracy of the scanner heights. After analysis, the REALM trajectory height shift was -0.05 meters.

Another procedure used to calibrate these data was to survey four cross lines perpendicular to the flight lines, two cross lines for each flight. Using TerraModel software, corrections to initial scanner parameters were found for roll, pitch, heading and mirror angle scale value. This process was repeated for all cross lines using the overlap area of the cross line, vehicle-mounted GPS ground truth, and survey lines; averaged solutions were used as the final calibration parameters.

7. Filtering and DEM Production

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

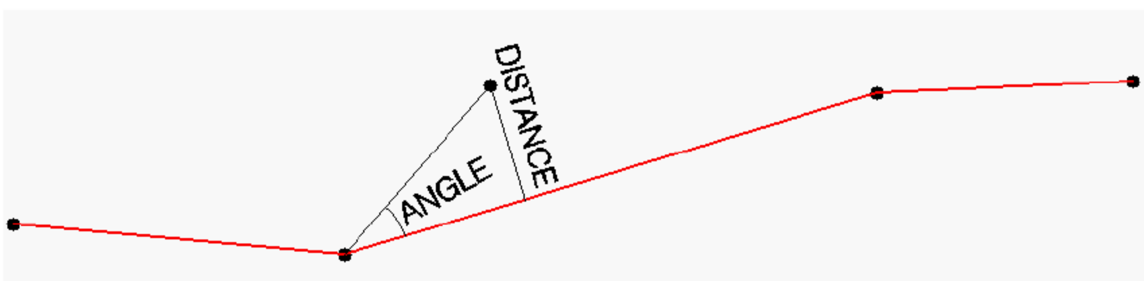
Two algorithms were run on the entire last return dataset:

1) Removal of "Low Points". This routine was used to search for possible error points which are clearly below the ground surface. The elevation of each point (=center) is compared with every other point within a given neighborhood and if the center point is clearly lower then any other point it will be classified as a "low point". This routine can also search for groups of low points where the whole group is lower than other points in the vicinity. The parameters used on this dataset were:

   Search for: Groups of Points
   Max Count (maximum size of a group of low points): 8
   More than (minimum height difference): 0.2 m
   Within (xy search range): 5.0 m

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 avoiding adding unnecessary point density into 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): 60.0 m
      Terrain Angle: 88.0
      Iteration Angle: 6.0
      Iteration Distance: 1.4 m
      Reduce iteration angle when edge length < : 5.0 m

After classification, the ground points were outputted in 2km x 2km tiles, ASCII format (XYZ). These tiles were reprocessed using in-house Perl scripts in order to provide tile overlap (100m) for accurate gridding .

Using the overlapping tiles, Digital Elevation Models were produced at 1.0 meter spacing using SURFER (Golden Software) ver. 9.01. Interpolation parameters were as follows:

Gridding Algorithm: Kriging
Variogram: Linear
Nugget Variance: 0.07 m
MicroVariance: 0.00 m
SearchDataPerSector: 10
SearchMinData: 5
SearchMaxEmpty: 1
SearchRadius: 40m

We used overlapping tiles for making sure that the surface obtained from krigging is consistent when transitioning from one tile to the adjacent tiles.

These 1m grids were afterwards imported in ESRI’s ArcINFO (ver. 8.3) GIS package, the overlap trimmed and then all grids were merged into one seamless raster dataset.

A similar tiling and krigging process was used to create the unfiltered seamless raster dataset, based on the unfiltered last return point data.

APPENDIX A.
GPS Reference Station Coordinates from OPUS

```
From: opus@ngs.noaa.gov
Sent: Thursday, June 09, 2005 12:35 PM
To: michaels@ufl.edu
Subject: OPUS solution : pine149z.05o 000318808

 FILE: pine149z.05o 000318808

                              NGS OPUS SOLUTION REPORT
                              ========================

      USER: michaels@ufl.edu                          DATE: June 09, 2005
RINEX FILE: pine149u.05o                              TIME: 16:34:59 UTC


  SOFTWARE: page5  0411.19 master.pl                 START: 2005/05/29  20:18:00
 EPHEMERIS: igr13250.eph [rapid]                      STOP: 2005/05/30  01:10:00
  NAV FILE: brdc1490.05n                          OBS USED: 10011 / 10383   :
96%
  ANT NAME: ASH700936D_M                       # FIXED AMB:    63 /    65   :
97%
ARP HEIGHT: 2.000                              OVERALL RMS: 0.016(m)


 REF FRAME: NAD_83(CORS96)(EPOCH:2002.0000)           ITRF00 (EPOCH:2005.4081)

         X:     -1707673.386(m)   0.015(m)         -1707674.106(m)   0.015(m)
         Y:     -3882902.112(m)   0.017(m)         -3882900.913(m)   0.017(m)
         Z:      4748636.887(m)   0.027(m)          4748636.934(m)   0.027(m)

       LAT:   48 25  3.26546      0.004(m)       48 25  3.28602      0.004(m)
     E LON:  246 15 37.58434      0.007(m)      246 15 37.52882      0.007(m)
     W LON:  113 44 22.41566      0.007(m)      113 44 22.47118      0.007(m)
    EL HGT:         1093.042(m)   0.035(m)             1092.541(m)   0.035(m)
 ORTHO HGT:         1107.833(m)   0.043(m) [Geoid03 NAVD88]

                         UTM COORDINATES    STATE PLANE COORDINATES
                          UTM (Zone 12)         SPC (2500 MT  )
Northing (Y) [meters]      5366339.528          471598.172
Easting (X)  [meters]       297304.868          286431.814
Convergence  [degrees]     -2.04988958         -3.10125589
Point Scale                 1.00010482          0.99969493
Combined Factor             0.99993352          0.99952371

US NATIONAL GRID DESIGNATOR: 12UTU9730566340(NAD 83)



                              BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
DG9747 MTFV FLAT HEAD COMMUNI CORS ARP     N481338.890 W1141936.543   48417.3
AJ1818 PLS1 POLSON 1 CORS ARP              N473949.553 W1140650.078   88356.3
DE8232 MSOL MISSOULA CORS ARP              N465545.837 W1140631.846  167790.6

                 NEAREST NGS PUBLISHED CONTROL POINT
TM0752      G 500                          N482507.    W1134413.        225.1
This position and these vector components were computed without any
knowledge by the National Geodetic Survey regarding the equipment or
```

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field operating procedures used.
From: opus@ngs.noaa.gov
Sent: Thursday, June 09, 2005 12:32 PM
To: michaels@ufl.edu
Subject: OPUS solution : Dand149z.05o 000318805

 FILE: Dand149z.05o 000318805

                              NGS OPUS SOLUTION REPORT
                              ========================

      USER: michaels@ufl.edu                          DATE: June 09, 2005
RINEX FILE: dand149v.05o                              TIME: 16:32:01 UTC


  SOFTWARE: page5  0411.19 master23.pl              START: 2005/05/29  21:02:00
 EPHEMERIS: igr13250.eph [rapid]                     STOP: 2005/05/30  01:24:00
  NAV FILE: brdc1490.05n                         OBS USED:  8791 /  8948   :
98%
  ANT NAME: ASH700936D_M                      # FIXED AMB:    31 /    33   :
94%
ARP HEIGHT: 2.000                             OVERALL RMS: 0.013(m)


 REF FRAME: NAD_83(CORS96)(EPOCH:2002.0000)            ITRF00 (EPOCH:2005.4081)

         X:     -1712319.013(m)   0.014(m)          -1712319.734(m)   0.014(m)
         Y:     -3876593.487(m)   0.015(m)          -3876592.289(m)   0.015(m)
         Z:      4751965.054(m)   0.016(m)           4751965.102(m)   0.016(m)

       LAT:   48 27 49.17326      0.006(m)        48 27 49.19379      0.006(m)
     E LON:  246 10  6.99683      0.016(m)       246 10  6.94117      0.016(m)
     W LON:  113 49 53.00317      0.016(m)       113 49 53.05883      0.016(m)
    EL HGT:          996.731(m)   0.020(m)               996.234(m)   0.020(m)
 ORTHO HGT:         1011.736(m)   0.032(m) [Geoid03 NAVD88]

                        UTM COORDINATES    STATE PLANE COORDINATES
                         UTM (Zone 12)         SPC (2500 MT  )
Northing (Y) [meters]     5371708.634           477085.092
Easting (X)  [meters]      290700.733           279929.868
Convergence  [degrees]    -2.12016062          -3.16842982
Point Scale                1.00013825           0.99971519
Combined Factor            0.99998204           0.99955905

US NATIONAL GRID DESIGNATOR: 12UTU9070171709(NAD 83)



                              BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
AJ1822 SPN1 SPOKANE 1 CORS ARP             N473106.062 W1172525.257  287967.6
AJ1818 PLS1 POLSON 1 CORS ARP              N473949.553 W1140650.078   91413.4
DE8232 MSOL MISSOULA CORS ARP              N465545.837 W1140631.846  171873.3

                 NEAREST NGS PUBLISHED CONTROL POINT
TM0758      A 500                          N482753.    W1134955.        125.2

This position and these vector components were computed without any
knowledge by the National Geodetic Survey regarding the equipment or
field operating procedures used.
```

```
From: opus@ngs.noaa.gov
Sent: Thursday, June 09, 2005 12:43 PM
To: michaels@ufl.edu
Subject: OPUS solution : pine150z.05o 000318809

 FILE: pine150z.05o 000318809

                              NGS OPUS SOLUTION REPORT
                              ========================

      USER: michaels@ufl.edu                         DATE: June 09, 2005
RINEX FILE: pine150o.05o                             TIME: 16:43:03 UTC


  SOFTWARE: page5  0411.19 master17.pl              START: 2005/05/30  14:18:00
 EPHEMERIS: igr13251.eph [rapid]                     STOP: 2005/05/30  20:15:00
  NAV FILE: brdc1500.05n                         OBS USED: 14069 / 14397   :
98%
  ANT NAME: ASH700936D_M                      # FIXED AMB:    58 /    58   :
100%
ARP HEIGHT: 2.000                             OVERALL RMS: 0.014(m)


 REF FRAME: NAD_83(CORS96)(EPOCH:2002.0000)           ITRF00 (EPOCH:2005.4102)

         X:     -1707673.366(m)   0.004(m)         -1707674.086(m)   0.004(m)
         Y:     -3882902.097(m)   0.005(m)         -3882900.898(m)   0.005(m)
         Z:      4748636.872(m)   0.023(m)          4748636.919(m)   0.023(m)

       LAT:   48 25  3.26566      0.013(m)        48 25  3.28623      0.013(m)
     E LON:  246 15 37.58493      0.006(m)       246 15 37.52941      0.006(m)
     W LON:  113 44 22.41507      0.006(m)       113 44 22.47059      0.006(m)
    EL HGT:         1093.017(m)   0.019(m)              1092.516(m)   0.019(m)
 ORTHO HGT:         1107.808(m)   0.031(m) [Geoid03 NAVD88]

                        UTM COORDINATES    STATE PLANE COORDINATES
                         UTM (Zone 12)        SPC (2500 MT  )
Northing (Y) [meters]     5366339.534          471598.177
Easting (X)  [meters]      297304.880          286431.826
Convergence  [degrees]    -2.04988946         -3.10125577
Point Scale                1.00010482          0.99969493
Combined Factor            0.99993353          0.99952371

US NATIONAL GRID DESIGNATOR: 12UTU9730566340(NAD 83)



                              BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
DG9747 MTFV FLAT HEAD COMMUNI CORS ARP     N481338.890 W1141936.543   48417.3
AJ1818 PLS1 POLSON 1 CORS ARP              N473949.553 W1140650.078   88356.3
DE8232 MSOL MISSOULA CORS ARP              N465545.837 W1140631.846  167790.6

                 NEAREST NGS PUBLISHED CONTROL POINT
TM0752      G 500                          N482507.    W1134413.        225.1

This position and these vector components were computed without any
knowledge by the National Geodetic Survey regarding the equipment or
field operating procedures used.
```

From: opus@NGS.NOAA.GOV
Sent: Thursday, June 09, 2005 12:37 PM
To: michaels@ufl.edu
Subject: OPUS solution : Dand150z.05o 000318806

```
 FILE: Dand150z.05o 000318806

                              NGS OPUS SOLUTION REPORT
                              ========================

      USER: michaels@ufl.edu                         DATE: June 09, 2005
RINEX FILE: dand150n.05o                             TIME: 16:36:41 UTC


  SOFTWARE: page5  0411.19 master28.pl              START: 2005/05/30  13:54:00
 EPHEMERIS: igr13251.eph [rapid]                     STOP: 2005/05/30  20:29:30
  NAV FILE: brdc1500.05n                         OBS USED: 15260 / 15446   :
99%
  ANT NAME: ASH700936D_M                      # FIXED AMB:    62 /    62   :
100%
ARP HEIGHT: 2.000                             OVERALL RMS: 0.012(m)


 REF FRAME: NAD_83(CORS96)(EPOCH:2002.0000)            ITRF00 (EPOCH:2005.4102)

         X:     -1712319.002(m)   0.003(m)          -1712319.723(m)   0.003(m)
         Y:     -3876593.473(m)   0.013(m)          -3876592.275(m)   0.013(m)
         Z:      4751965.027(m)   0.030(m)           4751965.075(m)   0.030(m)

       LAT:   48 27 49.17310      0.012(m)        48 27 49.19363      0.012(m)
     E LON:  246 10  6.99705      0.008(m)       246 10  6.94139      0.008(m)
     W LON:  113 49 53.00295      0.008(m)       113 49 53.05861      0.008(m)
    EL HGT:          996.699(m)   0.030(m)               996.202(m)   0.030(m)
 ORTHO HGT:         1011.704(m)   0.039(m) [Geoid03 NAVD88]

                        UTM COORDINATES    STATE PLANE COORDINATES
                         UTM (Zone 12)         SPC (2500 MT  )
Northing (Y) [meters]     5371708.629           477085.087
Easting (X)  [meters]      290700.737           279929.872
Convergence  [degrees]    -2.12016057          -3.16842978
Point Scale                1.00013825           0.99971519
Combined Factor            0.99998204           0.99955906

US NATIONAL GRID DESIGNATOR: 12UTU9070171709(NAD 83)



                              BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
DG9747 MTFV FLAT HEAD COMMUNI CORS ARP     N481338.890 W1141936.543   45155.5
AJ1818 PLS1 POLSON 1 CORS ARP              N473949.553 W1140650.078   91413.4
DE8232 MSOL MISSOULA CORS ARP              N465545.837 W1140631.846  171873.3

                 NEAREST NGS PUBLISHED CONTROL POINT
TM0758      A 500                          N482753.    W1134955.        125.2
```

This position and these vector components were computed without any knowledge by the National Geodetic Survey regarding the equipment or field operating procedures used.