LIDAR and Digital Imagery Mapping of Grand Canyon, Arizona

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AeroScan LIDAR and Digital Image Project
Grand Canyon, Arizona

EarthData Aviation was requested by the Grand Canyon Monitoring and Research Center to collect LIDAR and digital image data over the Grand Canyon. The data was to cover the Colorado River from Glen Canyon Dam to the headwaters of Lake Meade and cover a corridor of at least 1.35 kilometers wide centered on the river. In response, the project area was flown using EarthData Aviation's DeHavilland Twin Otter, tail number N824ED. The aircraft was equipped with the AeroScan LIDAR system, including an inertial measuring unit (IMU), and a dual frequency GPS receiver and antenna. The sensor system also includes a Kodak 4k panchromatic digital camera which is hard-mounted to the LIDAR unit. The project area was flown between March 27, 2000 and April 7, 2000.

Position and Orientation Data Collection and Processing

During the airborne data collection an additional GPS receiver was in constant operation over a National Geodetic Survey (NGS) control point. This point, designated "GCN E" (PID AC6806), is located at the Grand Canyon Airport and is the primary airport control station. Point "GCN E" is horizontal order B and third order class I vertical order. In addition, point "GCN E" was tied into the Grand Canyon control network by a GPS vector adjustment. The results showed agreement of better than 5 ppm between the NGS published coordinate and the coordinate derived from adjustment. During the data acquisition, the receiver on "GCN E" collected phase data at an epoch rate of 1 Hz.

Sta.	NAD 83 (1992) / WGS84		Ellip. Hgt.
GCN E	**35 57 51.18984**	**-112 08 01.12119**	**1994.89 m**

Coordinate position of the GPS base station

All GPS phase data was post processed with continuous kinematic survey techniques using "On the Fly" (OTF) integer ambiguity resolution. The GPS data was processed with forward and reverse processing algorithms. The results from each process were combined to yield a single fixed integer phase differential solution of the aircraft trajectory. Plots of altitude and the forward and reverse GPS solution residuals are attached for each day of flight. Spikes in the vertical component occur in turns and do not affect the integrity of the solution. The residual values are listed below:

Day of Flight	Horizontal Component Residual	Vertical Component Residual
March 27	+/- 5 cm	+/- 10 cm
March29	+/- 5 cm	+/- 10 cm
April 2	+/- 10 cm	+/- 20 cm
April 3	+/- 10 cm	+/- 10 cm
April 4	+/- 15 cm	+/- 25 cm
April 6	+/- 10 cm	+/- 15 cm
April 7	+/- 10 cm	+/- 10 cm

GPS Solution Forward and Reverse Residuals

A single IMU was used to record precise changes in position and orientation of the LIDAR scanner and digital camera at a rate of 50 Hz. All IMU data was processed post flight with a Kalman filter to integrate inertial measurements and precise phase differential GPS positions. The resulting solution contains geodetic position, omega, phi, kappa, and time for each photo center and also for subsequent merging with the laser ranging information.

Digital Photo Exterior Orientation Determination

A constant offset exists between the GPS unit, the IMU and the camera focal plane. Furthermore, each unit has its own coordinate reference frame. The GPS operates in the WGS84 coordinate frame, the IMU in the inertial frame, and the camera in its own body reference frame. The relationship between each of these components is determined through several geodetic processes including: survey measurements on the aircraft, comparison of the position and orientation as computed from an aerotriangulation solution over a boresight area, and results from the GPS/IMU solution. This process is performed once for each camera installation. The resultant alignment angles are used in the inertial solution to compute a set of exterior orientation parameters (X,Y,Z, ω, ϕ, κ) for all photographs.

LIDAR Data Collection and Processing

The tables below show the flight characteristics and sensor settings used during data acquisition.

Flying Height	3048 m AMT
Airspeed	75 – 125 knots
Laser Pulse Rate	15 kHz
Field of View	25°
Scan Rate	13 Hz
Average Swath Width	1351 m
Average Post Spacing	3.75 m

LIDAR, IMU, and GPS data were correlated using GPS time and processed using LIDAR post-processing software to determine the coordinate of each point on the ground. The AeroScan LIDAR is able to receive up to five returns from each laser shot fired. This allows receipt of return data from multiple objects as the laser beam travels towards the ground. For example, in a vegetated area, the laser beam may first hit the leaves of a tree (generating Return 1), then a branch (generating Return 2), and finally the ground (generating Return 3). This sequence may continue for up to five returns. All ranges have been corrected for atmospheric refraction and transmission delays. The resulting three dimensional coordinates are compiled in an ASCII mass point file of x, y, z on the UTM projection.

Initial evaluation of the LIDAR data included the comparison of the data from the flight lines to a kinematic survey performed in 1998 around Glenn Canyon Dam. Comparisons were also

performed between areas of overlap around adjoining flight lines. The comparison to the kinematic survey provided the following results:

Comparison to Kinematic Survey:

Vertical Accuracy	15.4 cm RMSE
Standard Deviation	15.3 cm
Mean Difference	-2 cm
Number of Points in Sample	231

The data were also compared to USGS control points that were located in the area. Five control points were found within the data collected on March 27th. Four of these five points matched extremely well with the LIDAR data. However one, GP0075, does not agree as well. Below are summaries of two scenarios, the first one includes point GP0075 and the second one does not.

Comparison to USGS Control Points (Including point GP0075):

Vertical Accuracy	16.7 cm RMSE
Standard Deviation	16.1 cm
Mean Difference	-8 cm
Number of Points in Sample	5

Comparison to USGS Control Points (Excluding point GP0075):

Vertical Accuracy	3.1 cm RMSE
Standard Deviation	3.1 cm
Mean Difference	-1.5 cm
Number of Points in Sample	4

In addition, the data from the flight lines were compared to a series of control points inside the canyon that were supplied by the Grand Canyon Monitoring and Research Center. When these points were compared, some of them agreed closely as shown below. However, there were many that either did not compare well or could not be compared at all.

We believe that these problems can be attributed to a combination of two factors, the LIDAR accuracy check software and the local terrain. The software that is used to check data accuracy uses interpolation to calculate the elevation at a specific location. In the case of the Grand Canyon data, we ran into two main problems. First, the LIDAR does not receive return data from water. If an interpolation is done in an area consisting of mostly water, there may not be enough neighboring points within the search area to perform the interpolation. The second major problem was that the interpolation provided a final elevation that did not match the control point elevation. Again, we believe that this discrepancy can be attributed to the interpolation. With the steep and rocky terrain, a point very near the control point horizontally may have an elevation that is very different. Therefore the interpolated elevation does not agree. To help check this theory, we examined the points that were used in the interpolation for each control point. In the majority of the cases when the search radius was extended to three meters, there were points used in the interpolation that fell within +/-25 cm of the control point elevation.

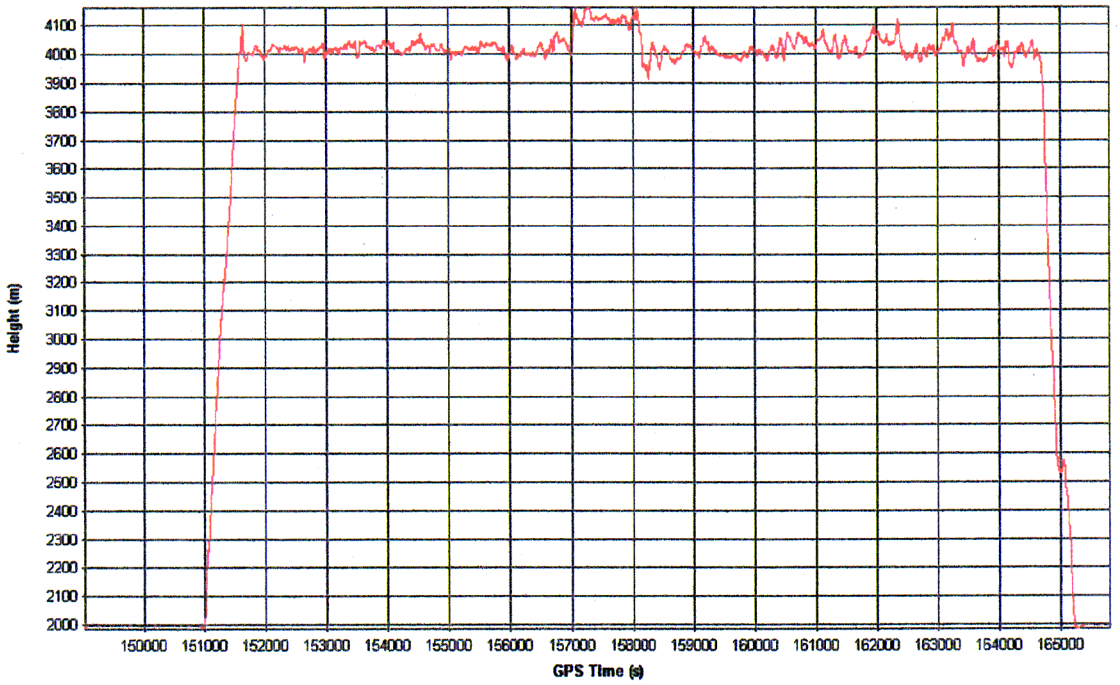
The following list shows points that matched well in our accuracy check software:

Comparison of Grand Canyon Control to LIDAR Points			
Point ID	**Elevation Provided (m)**	**Interpolated Elevation (m)**	**Difference (m)**
3	949.127	948.987	0.140
6	935.725	935.920	-0.195
9	930.446	930.500	-0.054
13	923.967	924.047	-0.080
14	923.073	923.060	0.013
17	911.464	911.333	0.131
22	898.983	898.820	0.163
26	891.912	892.071	-0.159
27	881.558	881.736	-0.178
28	881.382	881.850	-0.193
32	862.263	862.400	-0.137
2	954.128	954.060	0.068
31	863.181	863.250	-0.069
36	852.250	852.380	-0.130
38	851.065	851.073	-0.008
43	835.801	835.680	0.121
44	829.602	829.650	-0.048
55	788.166	788.280	-0.114
47	816.301	816.202	-0.001
16	919.408	919.510	-0.102
61	617.586	617.646	-0.060
82	385.539	385.560	-0.021
79	389.709	389.480	0.229
80	388.164	387.912	0.252
71	504.823	505.017	-0.194
81	387.105	387.317	-0.212
75	428.757	428.500	0.257
77	416.124	416.232	-0.108

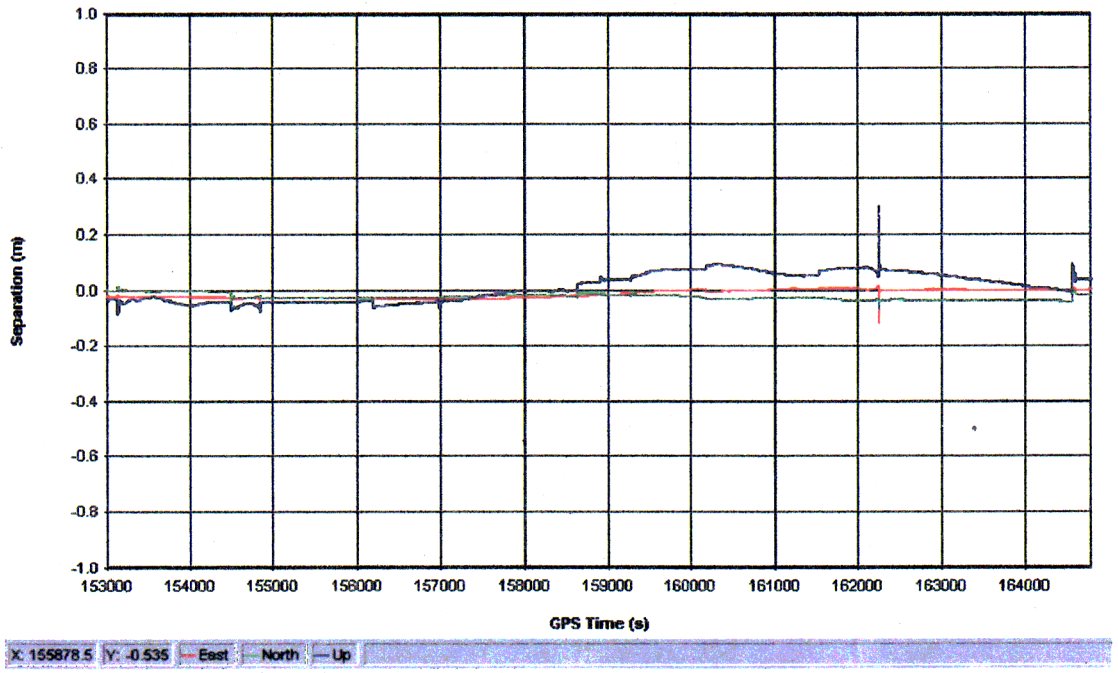
When the points used in the interpolation were examined, the results were as follows:

Points with at least one point used in the interpolation falling within 15 cm of the known control point elevation.	1,2,3,6,8,9,10,11,13,14,16,17,19,20,21,22,26,27,30,31,32, 35,36,37,38,41, 42,44,45, 47,50,51,52,53,54,55,56,57, 71, 81, 61, 62, 66, 68, 69, 79, 82
Points with at least one point used in the interpolation falling 15-30 cm from the known control point elevation.	5,23,25,28,29,34,36,39,40,49, 84, 65, 67, 80, 74

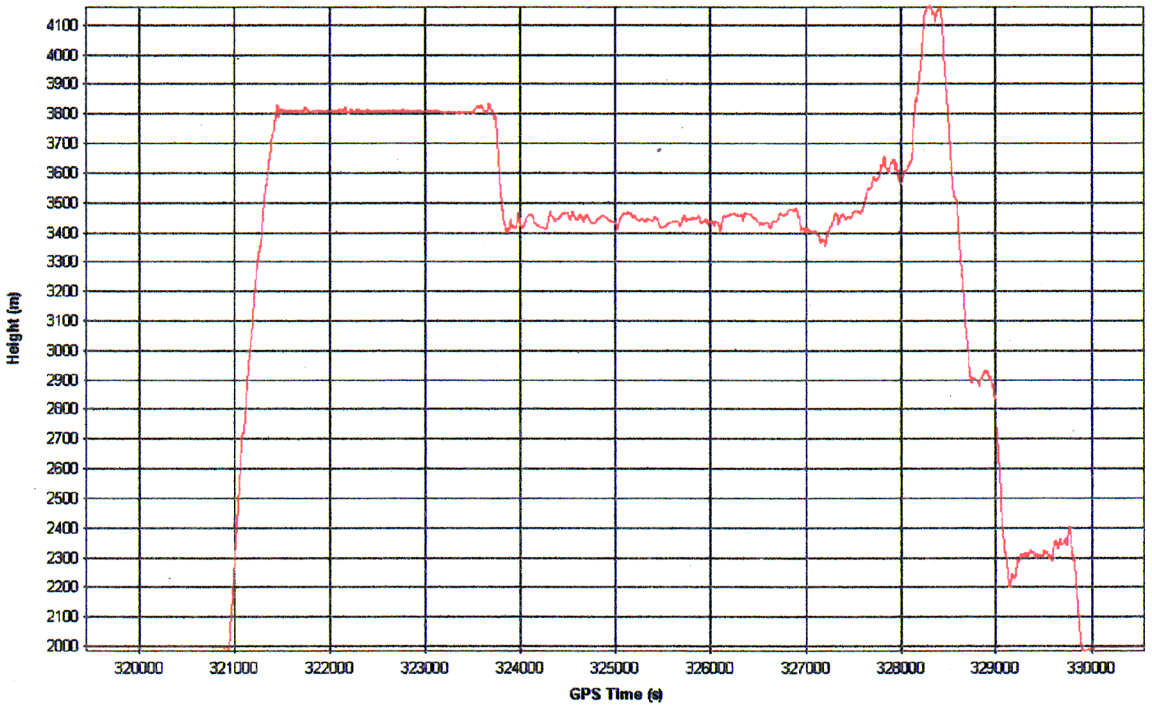
NOTE: The search radius was 3 meters



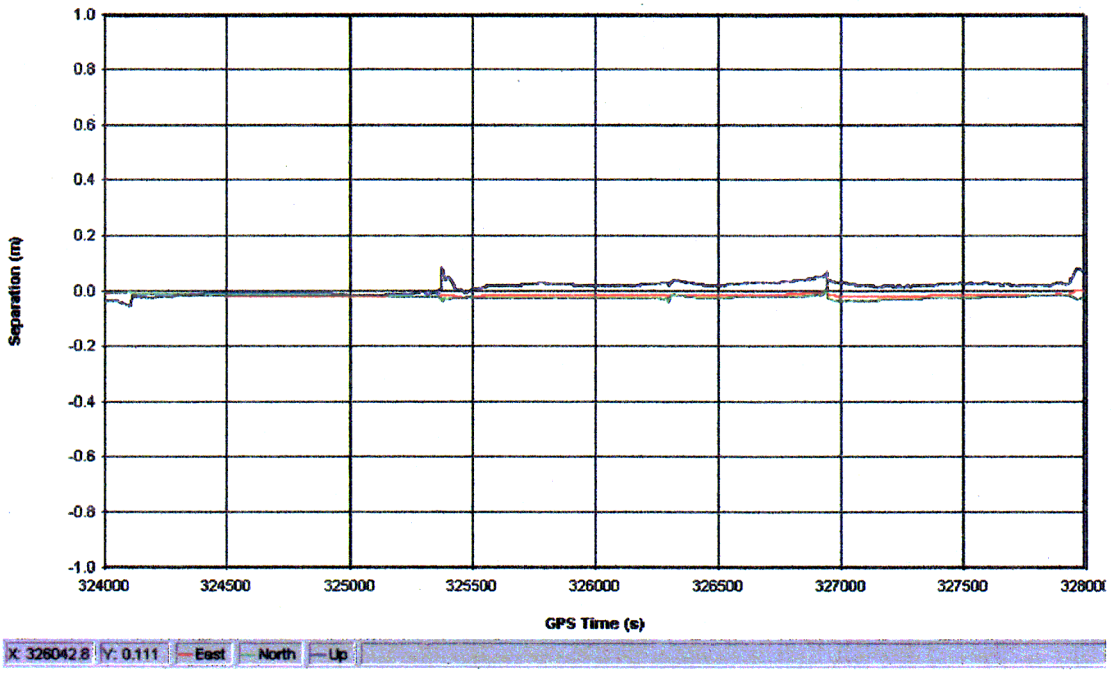
Altitude Plot (March 27)



Forward-Reverse Solution Residuals (March 27)



Altitude Plot (March 29)



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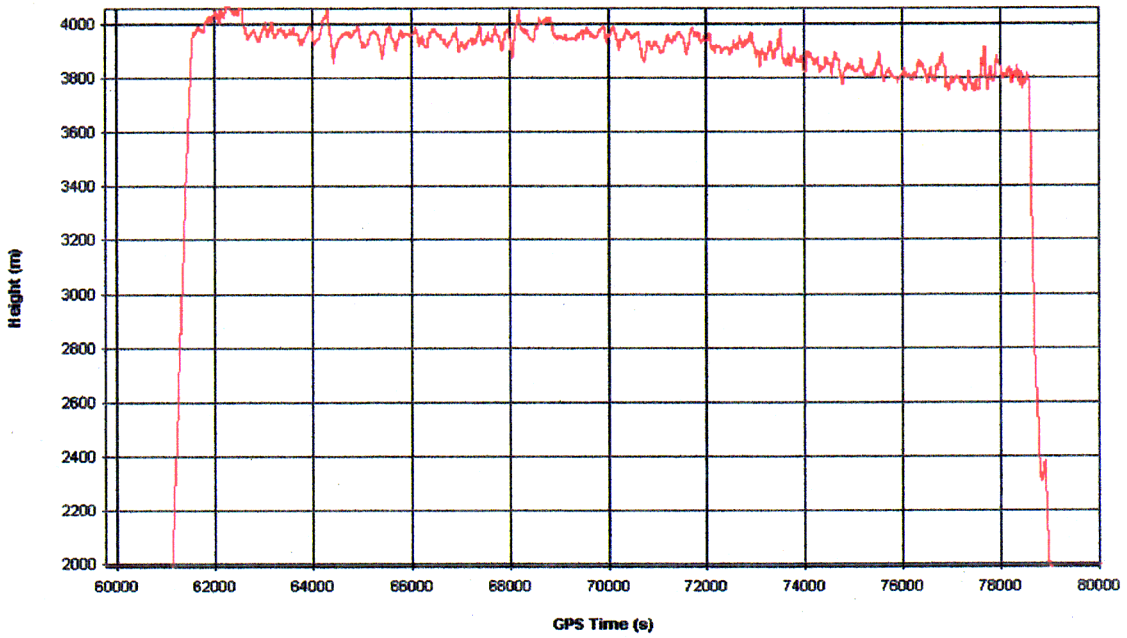
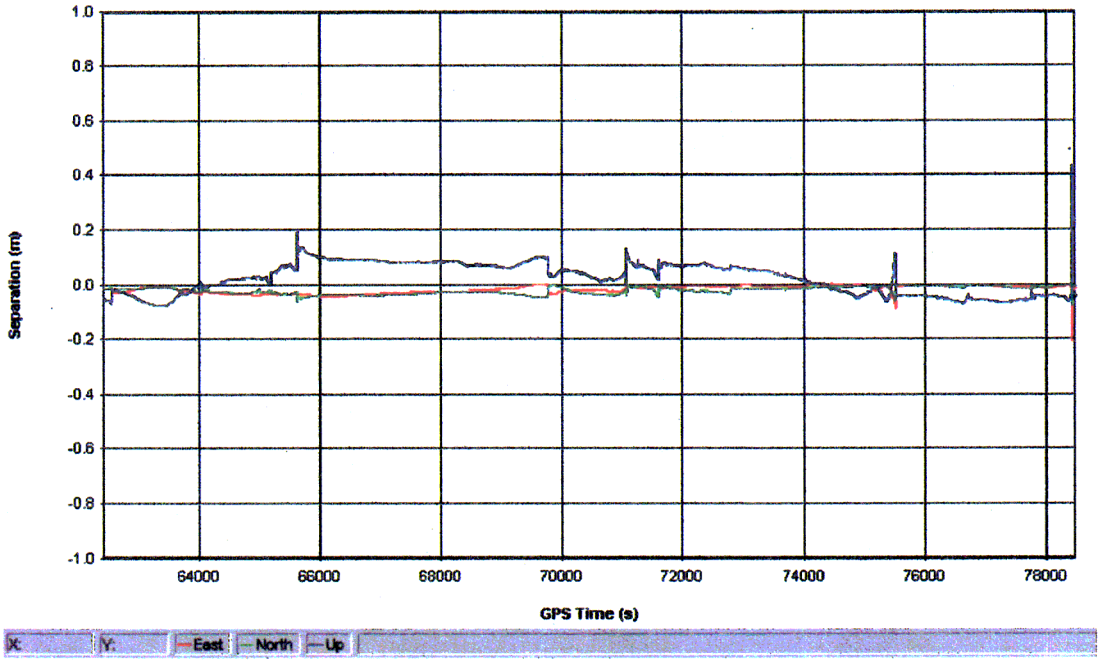
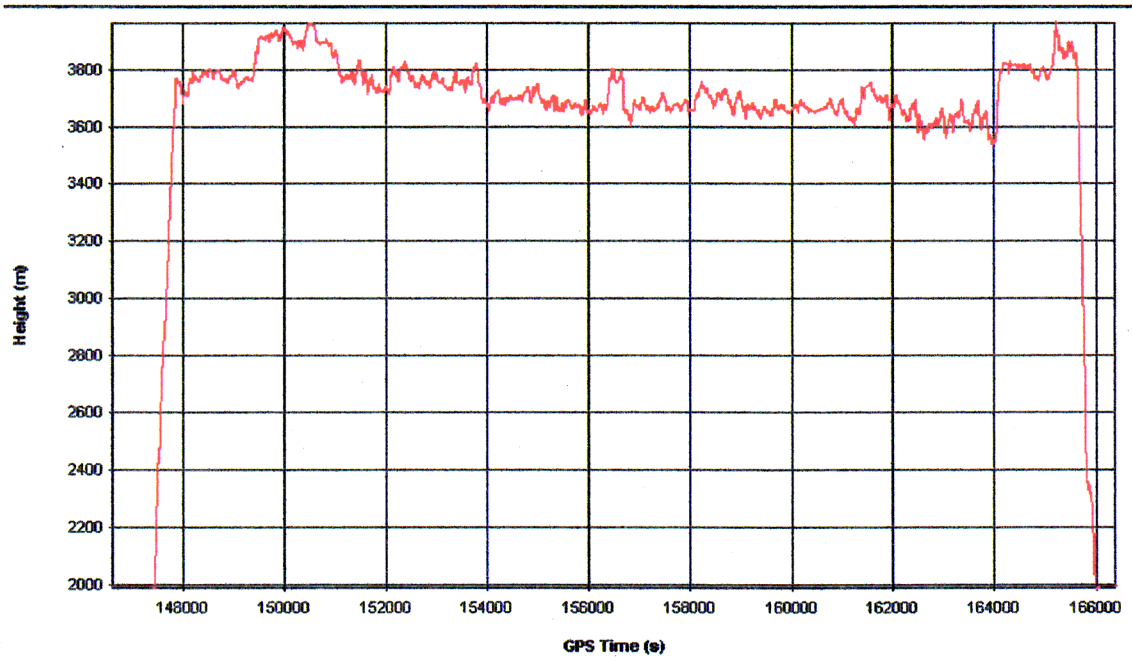


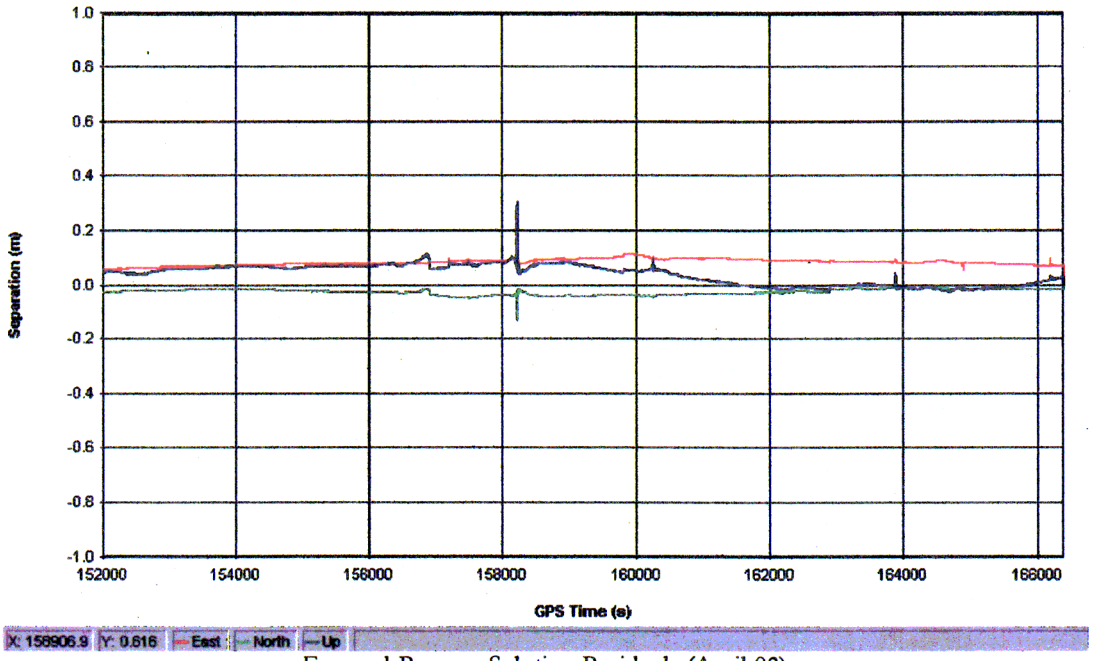
Altitude Plot (April 02)



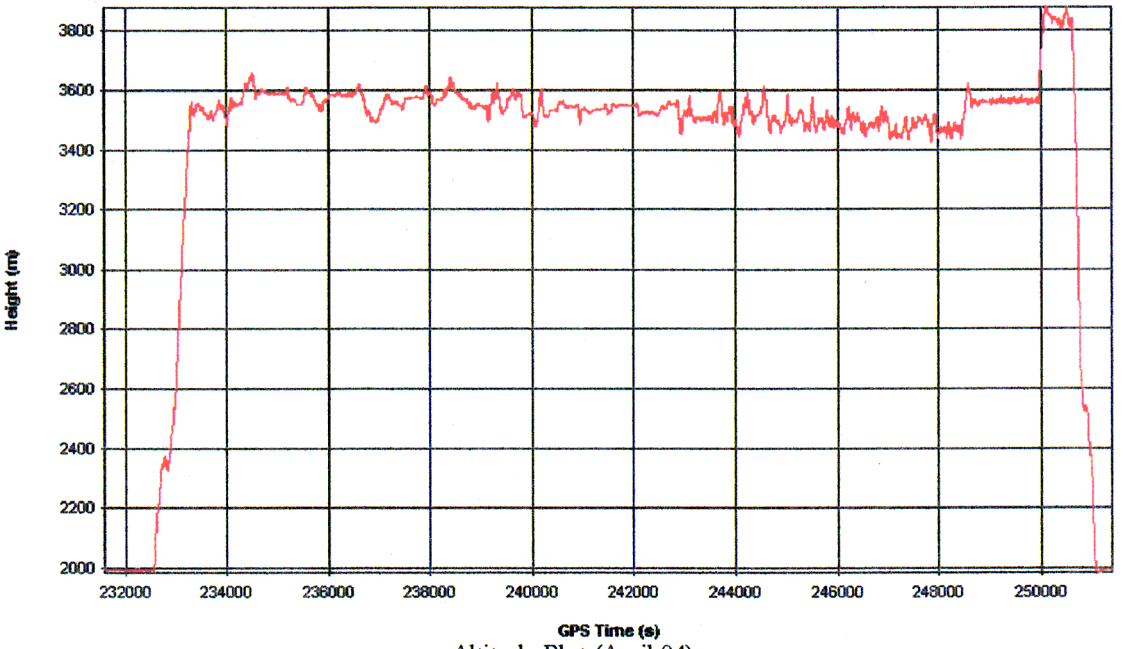
Forward-Reverse Solution Residuals (April 02)



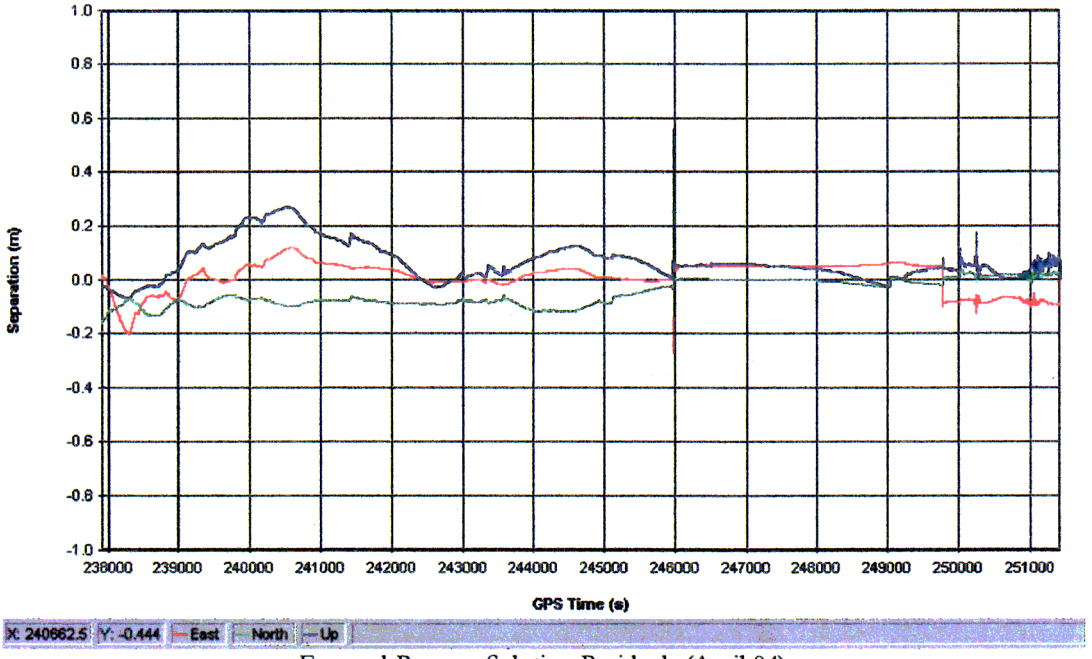
Altitude Plot (April 03)



Forward-Reverse Solution Residuals (April 03)



Altitude Plot (April 04)



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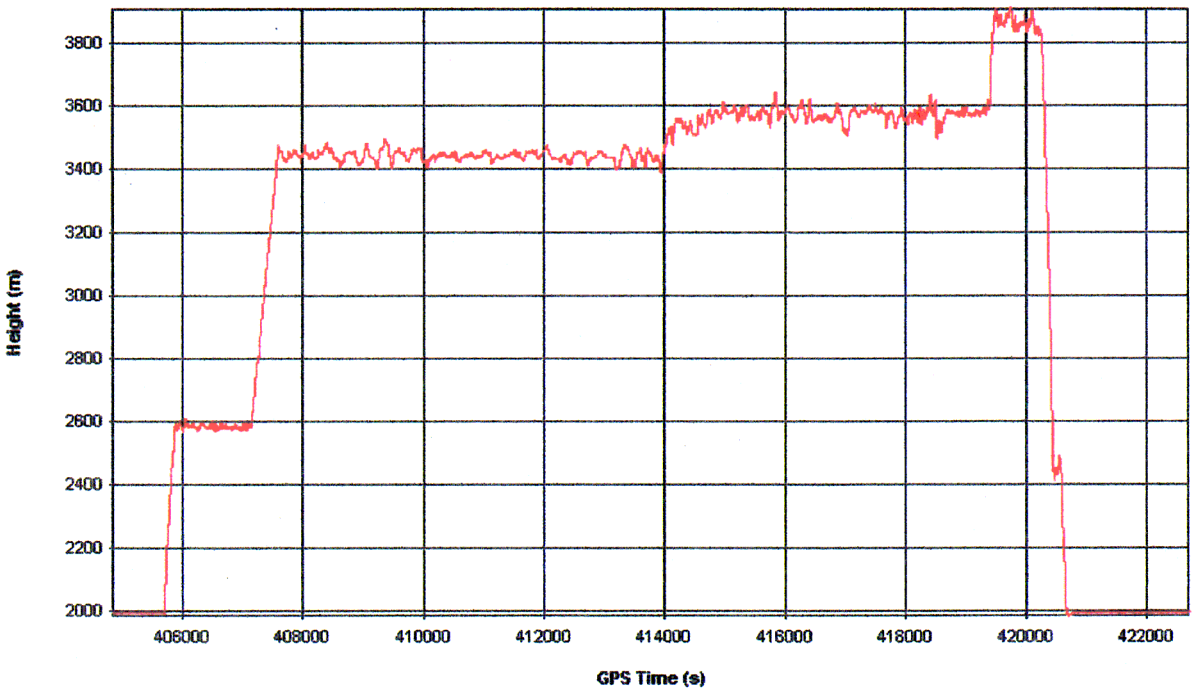

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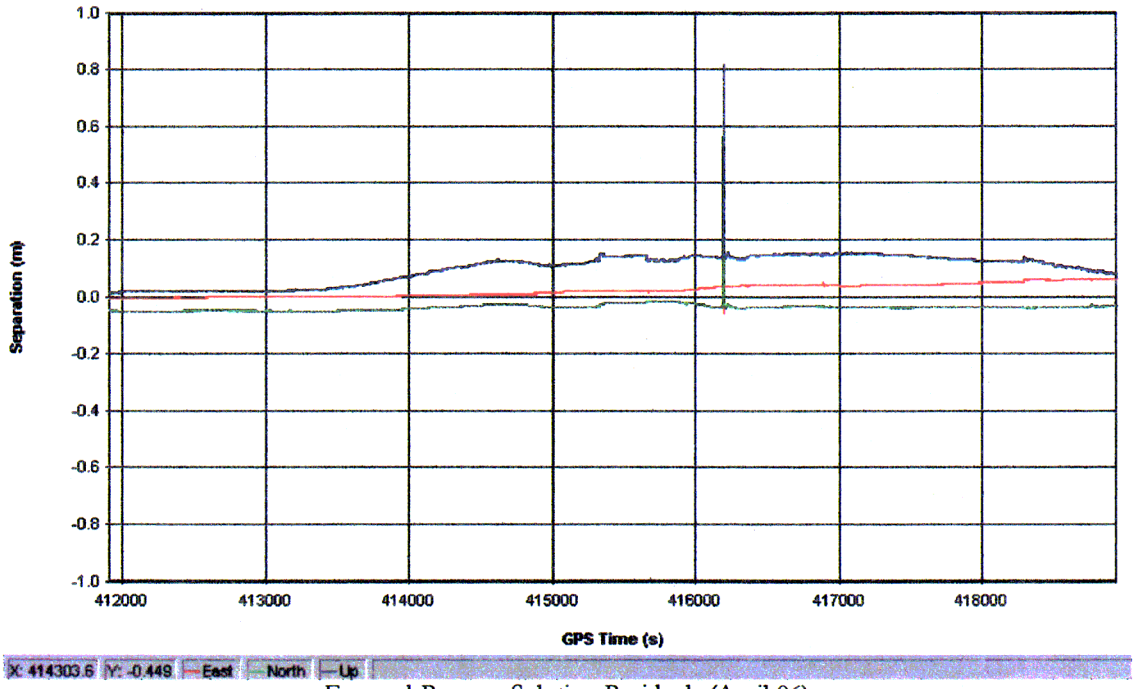
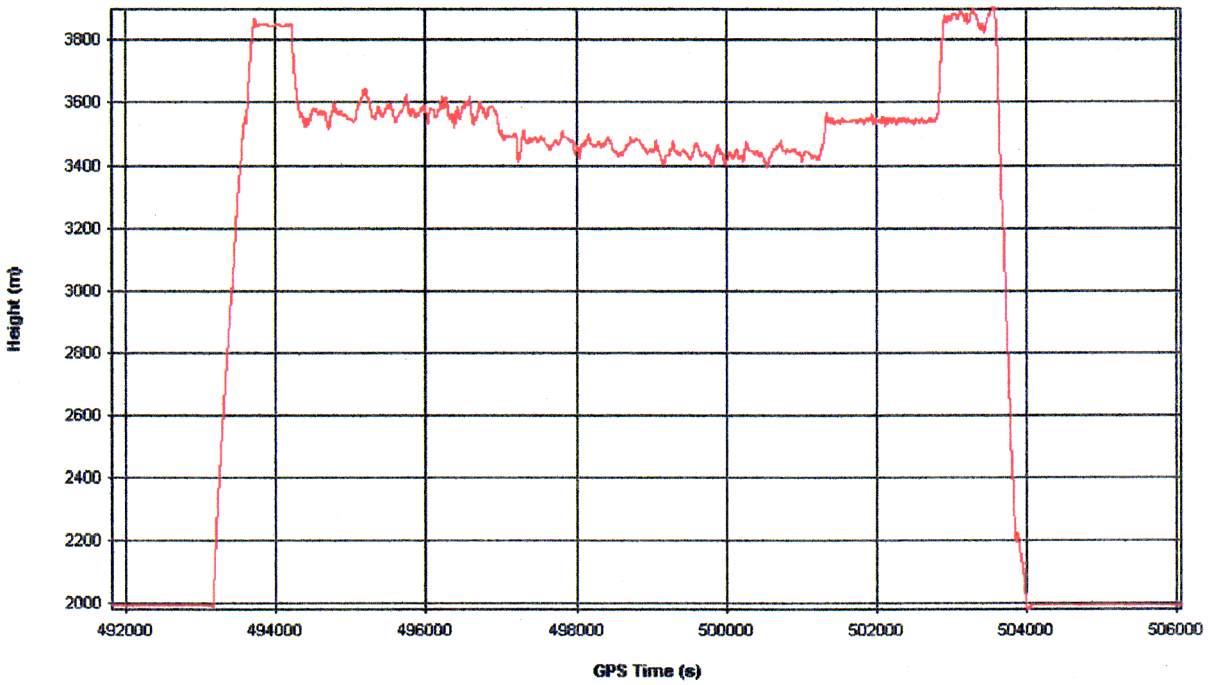
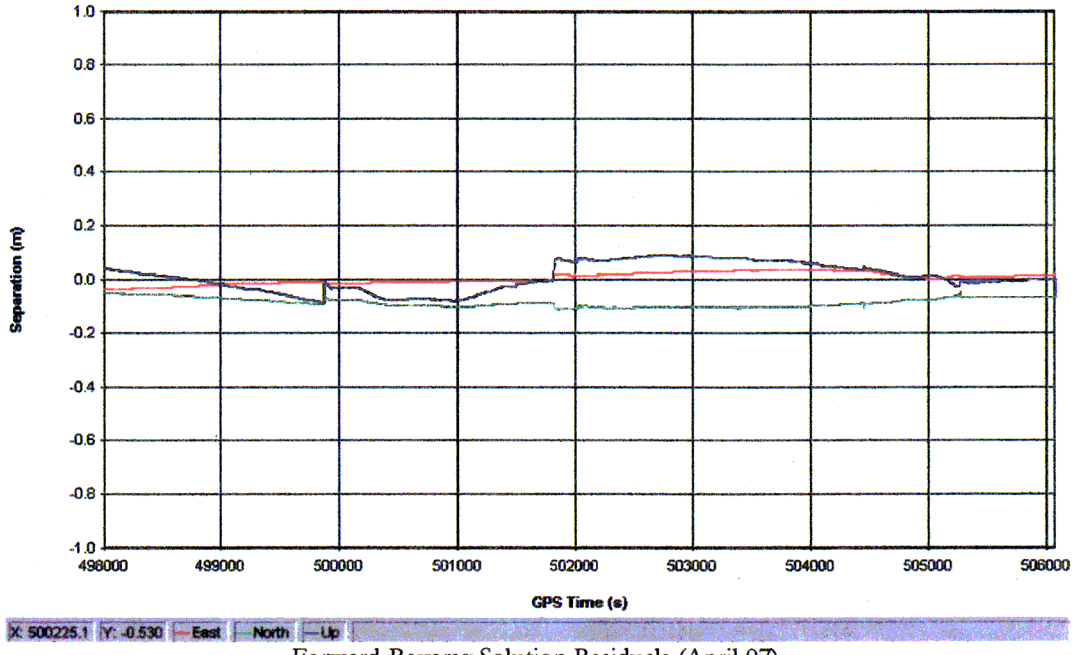


Forward-Reverse Solution Residuals (April 06)



Altitude Plot (April 07)



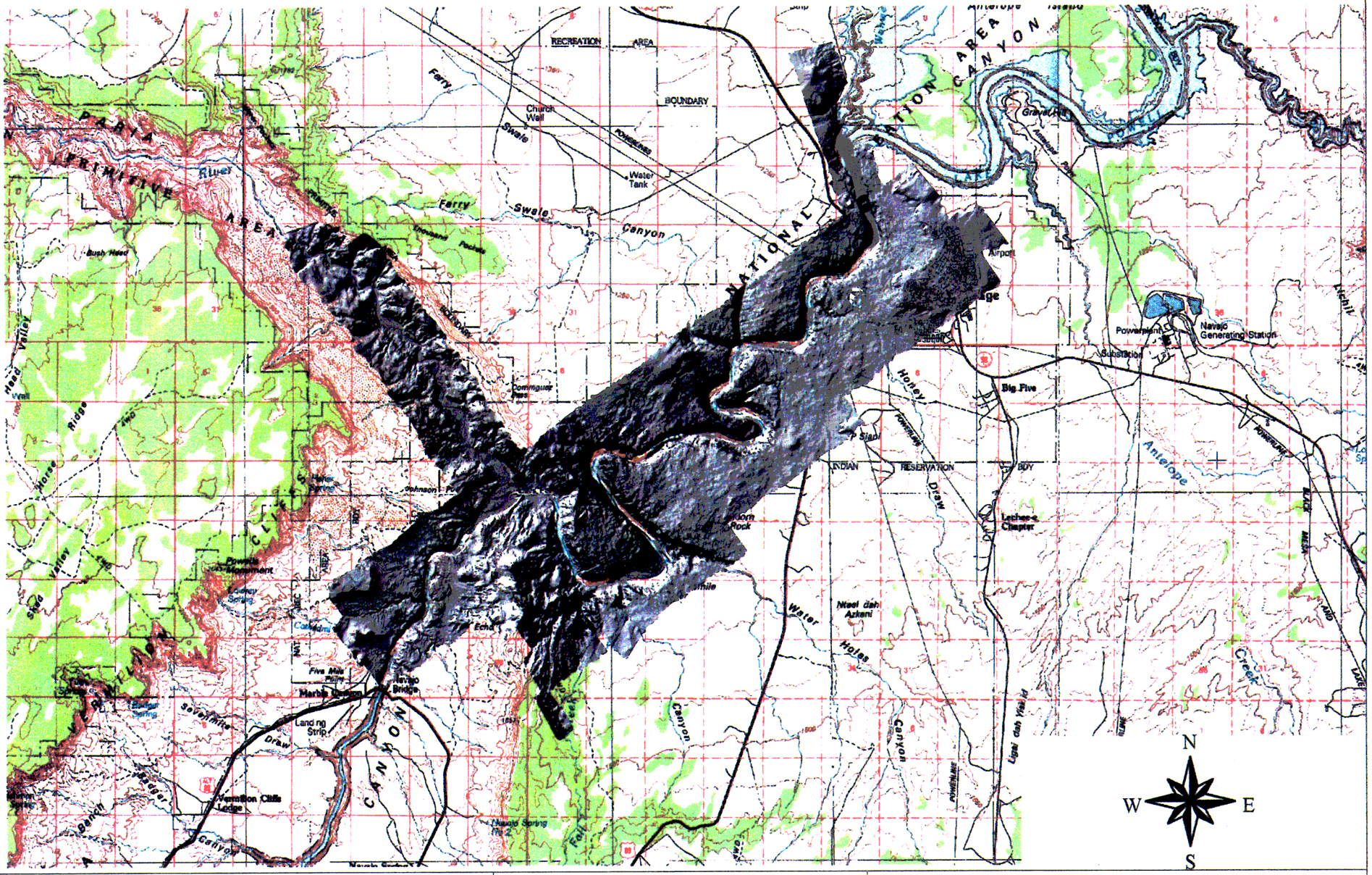
Forward-Reverse Solution Residuals (April 07)

```
Data Sheet RetrievalThe NGS Data Sheet
DATABASE = Sybase ,PROGRAM = datasheet, VERSION = 6.23
Starting Datasheet Retrieval...
1        National Geodetic Survey,    Retrieval Date = JULY 20, 2000
 AC6806
**********************************************************************
 AC6806  PACS         -  This is a Primary Airport Control Station.
 AC6806  DESIGNATION  -  GCN E
 AC6806  PID          -  AC6806
 AC6806  STATE/COUNTY-  AZ/COCONINO
 AC6806  USGS QUAD    -  TUSAYAN WEST (1979)
 AC6806
 AC6806                          *CURRENT SURVEY CONTROL
 AC6806 ______________________________________________________________________
 AC6806* NAD 83(1992)-  35 57 51.18984(N)     112 08 01.12119(W)      ADJUSTED
 AC6806* NAVD 88      -       2017.62   (meters)     6619.5    (feet)  GPS OBS
 AC6806 ______________________________________________________________________
 AC6806  X            -  -1,947,871.600 (meters)                      COMP
 AC6806  Y            -  -4,788,960.012 (meters)                      COMP
 AC6806  Z            -   3,726,150.573 (meters)                      COMP
 AC6806  LAPLACE CORR-             1.54  (seconds)                     DEFLEC99
 AC6806  ELLIP HEIGHT-          1994.89  (meters)                      GPS OBS
 AC6806  GEOID HEIGHT-           -22.85  (meters)                      GEOID99
 AC6806
 AC6806  HORZ ORDER  -  B
 AC6806  ELLP ORDER  -  THIRD      CLASS I
 AC6806
 AC6806.This mark is at Grand Canyon Natl Park Airport (GCN)
 AC6806
 AC6806.The horizontal coordinates were established by GPS observations
 AC6806.and adjusted by the National Geodetic Survey in March 1997.
 AC6806
 AC6806.The orthometric height was determined by GPS observations and a
 AC6806.high-resolution geoid model.
 AC6806
 AC6806.GPS derived orthometric heights for airport stations designated as
 AC6806.PACS or SACS are published to 2 decimal places.  This maintains
 AC6806.centimeter relative accuracy between the PACS and SACS.  It does
 AC6806.not indicate centimeter accuracy relative to other marks which are
 AC6806.part of the NAVD 88 network.
 AC6806
 AC6806.The X, Y, and Z were computed from the position and the ellipsoidal
ht.
 AC6806
 AC6806.The Laplace correction was computed from DEFLEC99 derived deflections.
 AC6806
 AC6806.The ellipsoidal height was determined by GPS observations
 AC6806.and is referenced to NAD 83.
 AC6806
 AC6806.The geoid height was determined by GEOID99.
 AC6806
 AC6806;                    North          East      Units   Scale       Converg.
 AC6806;SPC AZ C      -   550,564.882   193,789.563   MT  0.99990472 -0 07 38.7
 AC6806;UTM  12       - 3,980,573.813   397,779.070   MT  0.99972875 -0 39 57.0
 AC6806
```

```
AC6806|-----------------------------------------------------------------------|
AC6806| PID    Reference Object                          Distance      Geod. Az  |
AC6806|                                                                dddmmss.s |
AC6806| AE3162 GCN E1                                    23.328 METERS 06214     |
AC6806|-----------------------------------------------------------------------|
AC6806
AC6806                              SUPERSEDED SURVEY CONTROL
AC6806
AC6806.No superseded survey control is available for this station.
AC6806
AC6806_MARKER: I = METAL ROD
AC6806_SETTING: 49 = STAINLESS STEEL ROD W/O SLEEVE (10 FT.+)
AC6806_STAMPING: GCN E 1996
AC6806_PROJECTION: FLUSH
AC6806_MAGNETIC: I = MARKER IS A STEEL ROD
AC6806_STABILITY: B = PROBABLY HOLD POSITION/ELEVATION WELL
AC6806_SATELLITE: THE SITE LOCATION WAS REPORTED AS SUITABLE FOR
AC6806+SATELLITE: SATELLITE OBSERVATIONS - May 02, 1997
AC6806_ROD/PIPE-DEPTH: 2.80 meters
AC6806
AC6806  HISTORY      - Date     Condition        Recov. By
AC6806  HISTORY      - 1996     MONUMENTED       CHANCE
AC6806  HISTORY      - 19970502 GOOD    .        NGS
AC6806
AC6806                              STATION DESCRIPTION
AC6806
AC6806'DESCRIBED BY JE CHANCE AND ASSOCIATES 1996 (SDC)
AC6806'THE STATION IS LOCATED APPROXIMATELY 11.2 KM (6.95 MI) SOUTH-SOUTHWEST
AC6806'OF THE TOWN OF GRAND CANYON, APPROXIMATELY 3.2 KM (2.00 MI) SOUTHWEST
AC6806'OF THE TOWN OF TUSAYAN AT THE GRAND CANYON NATIONAL PARK AIRPORT.
AC6806'OWNERSHIP -- STATE OF ARIZONA, RUSSELL PANKEY - OPERATIONS SUPERVISOR,
AC6806'PHONE (602) 638-2446 TO REACH THE STATION FROM THE INTERSECTION OF US
AC6806'HIGHWAY 180 AND THE SOUTHERN BOUNDARY OF GRAND CANYON NATIONAL PARK,
AC6806'PROCEED SOUTH ON US HIGHWAY 180 (STATE HIGHWAY 64) FOR 4.0 KM (2.50
AC6806'MI) TO THE JUNCTION WITH THE AIRPORT ROAD ON THE RIGHT AT HIGHWAY
AC6806'MILEPOST 235.2.  TURN RIGHT AND GO WESTERLY FOR 0.3 KM (0.20 MI) TO
AC6806'ENTRANCE GATE 7 AND A ROAD ON THE RIGHT LEADING TO THE CONTROL TOWER.
AC6806'PROCEED THROUGH GATE TO STATION ON THE LEFT THE STATION IS THE TOP
AC6806'CENTER OF A STAINLESS STEEL ROD DRIVEN TO REFUSAL AT A DEPTH OF 2.80 M
AC6806'(9.19 FT) RECESSED 7 CM BELOW GROUND LEVEL IN A 2.5 CM DIA GREASE
AC6806'FILLED FINNED PLASTIC SLEEVE 90 CM LONG ENCASED IN A 12.7 CM DIA PVC
AC6806'PIPE WITH NGS LOGO CAP SURROUNDED BY CONCRETE.  THE LOGO CAP AND
AC6806'CONCRETE ARE SET FLUSH WITH THE GROUND. THE STATION IS LOCATED 21.80 M
AC6806'(71.52 FT) SOUTHWEST OF THE CORNER FENCEPOST, 8.95 M (29.36 FT)
AC6806'WEST-SOUTHWEST OF THE SOUTHWEST CORNER OF THE CONCRETE BASE FOR THE
AC6806'ELECTRIC GATE POWER BOX, 6.40 M (21.00 FT) NORTHWEST OF THE
AC6806'SOUTHWEST-NORTHEAST FENCELINE, 11.25 M (36.91 FT) SOUTH-SOUTHWEST OF
AC6806'THE CENTERLINE OF THE ROAD LEADING TO THE CONTROL TOWER AT A SEWER
AC6806'MANHOLE, 31.0 M (101.7 FT) NORTHWEST OF THE CENTERLINE OF THE ROAD TO
AC6806'THE TERMINAL, AND 0.9 M (3.0 FT) NORTH-NORTHEAST OF A CARSONITE
AC6806'WITNESS POST THE STATION IS DESIGNATED AS A PRIMARY AIRPORT CONTROL
AC6806'STATION (PACS) - ARIZONA ANA SURVEYS 1996
AC6806
AC6806                              STATION RECOVERY (1997)
AC6806
```

AC6806'RECOVERY NOTE BY NATIONAL GEODETIC SURVEY 1997 (AJL)
AC6806'THE STATION IS LOCATED ABOUT 3.2 KM (2.00 MI) SOUTH OF THE TOWN OF
AC6806'TUSAYAN AT THE GRAND CANYON NATIONAL PARK AIRPORT. OWNERSHIP--ARIZONA
AC6806'DEPARTMENT OF TRANSPORTATION, AIRPORT MANAGER IS JOE ROUSSEL, GRAND
AC6806'CANYON NATIONAL PARK AIRPORT, P O BOX 3188, GRAND CANYON, AZ 86023.
AC6806'THE PHONE NUMBER IS (520) 638-2446. TO REACH THE STATION FROM THE
AC6806'SOUTHERN BOUNDARY OF THE GRAND CANYON NATIONAL PARK AND STATE HIGHWAY
AC6806'64, GO SOUTHERLY ON THE HIGHWAY (PASSING THROUGH THE TOWN OF TUSAYAN)
AC6806'FOR 3.8 KM (2.35 MI) TO THE NORTH ENTRANCE OF THE AIRPORT ON THE
AC6806'RIGHT. TURN RIGHT AND GO WESTERLY FOR 0.3 KM (0.20 MI) TO THE AIR
AC6806'TRAFFIC CONTROL TOWER ACCESS ROAD AT GATE 7 (LOCKED) ON THE RIGHT.
AC6806'TURN RIGHT AND GO WEST FOR 50-METERS ON THE ACCESS ROAD TO THE STATION
AC6806'LEFT JUST AFTER PASSING THROUGH THE GATE. THE STATION IS LOCATED 31.0
AC6806'M (101.7 FT) NORTHWEST OF THE CENTER OF THE ENTRANCE ROAD LANES
AC6806'LEADING TO THE TERMINAL, 11.3 M (37.1 FT) SOUTHWEST OF THE CENTER OF
AC6806'THE AIR TRAFFIC CONTROL TOWER ENTRANCE ROAD AT A MANHOLE, 9.0 M (29.5
AC6806'FT) WEST-SOUTHWEST OF THE SOUTHWEST CORNER OF THE CONCRETE BASE FOR
AC6806'THE ELECTRIC GATE POWER BOX, AND 0.9 M (3.0 FT) NORTH-NORTHEAST OF A
AC6806'FIBERGLASS WITNESS POST. NOTE--THIS STATION DESIGNATED AS A PACS.

*** retrieval complete.
Elapsed Time = 00:00:02



EARTHDATA AVIATION

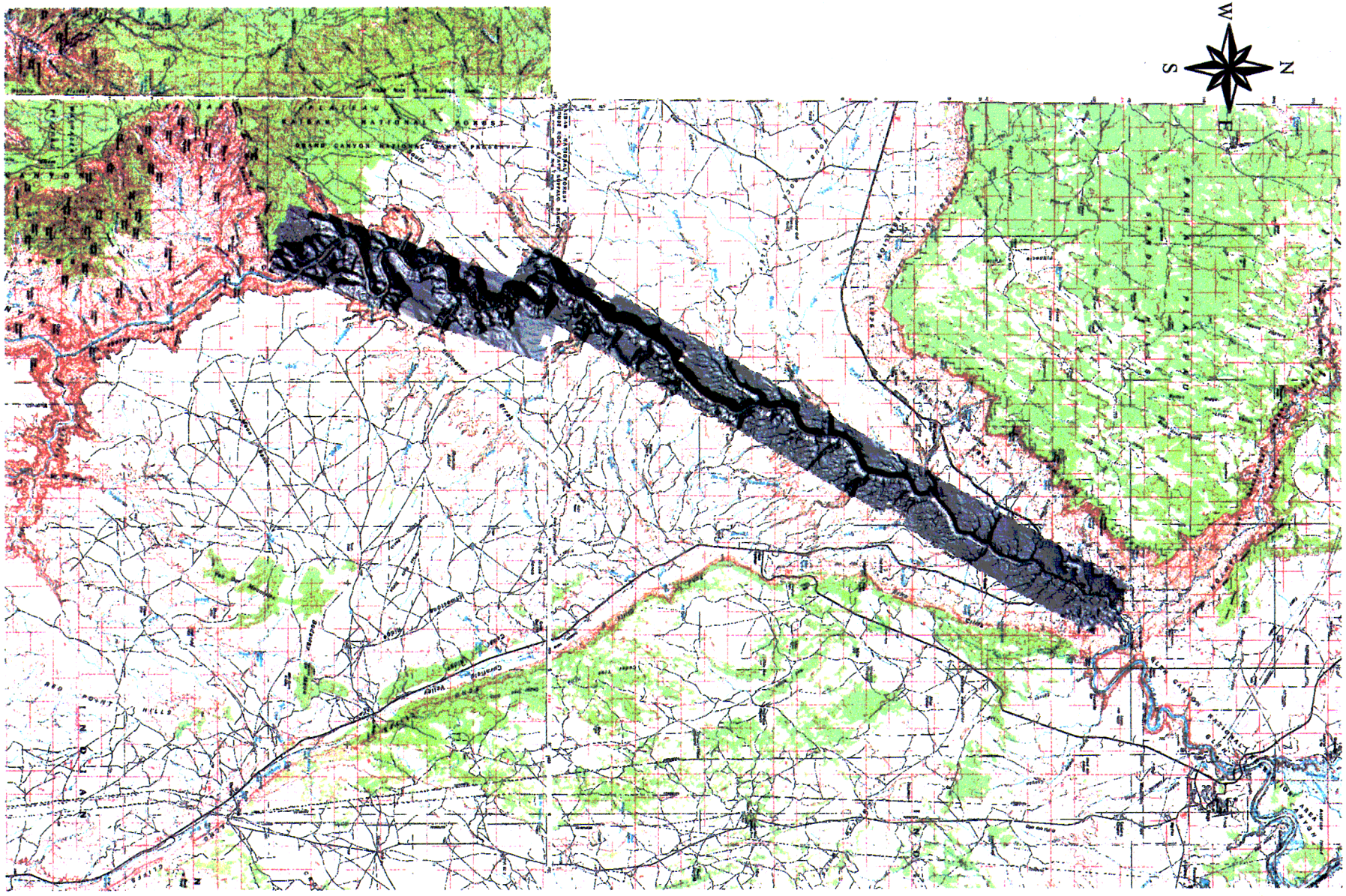
18227 AIRPARK DRIVE-HAGERSTOWN-MARYLAND-21742

EarthData Job Number: EA 00145	
Flight Date: March 27, 2000	
UTM Zone 12	
1% of Data Collected Displayed	
Reference Exhibit Only	

Grand Canyon LIDAR Scan Coverage

Date: June 17, 2000

Exhibit: # 1



EARTHDATA
AVIATION

18227 AIRPARK DRIVE-HAGERSTOWN-MARYLAND-21742

EarthData Job Number: EA 00145

Flight Date: March 27, 2000

UTM Zone 12

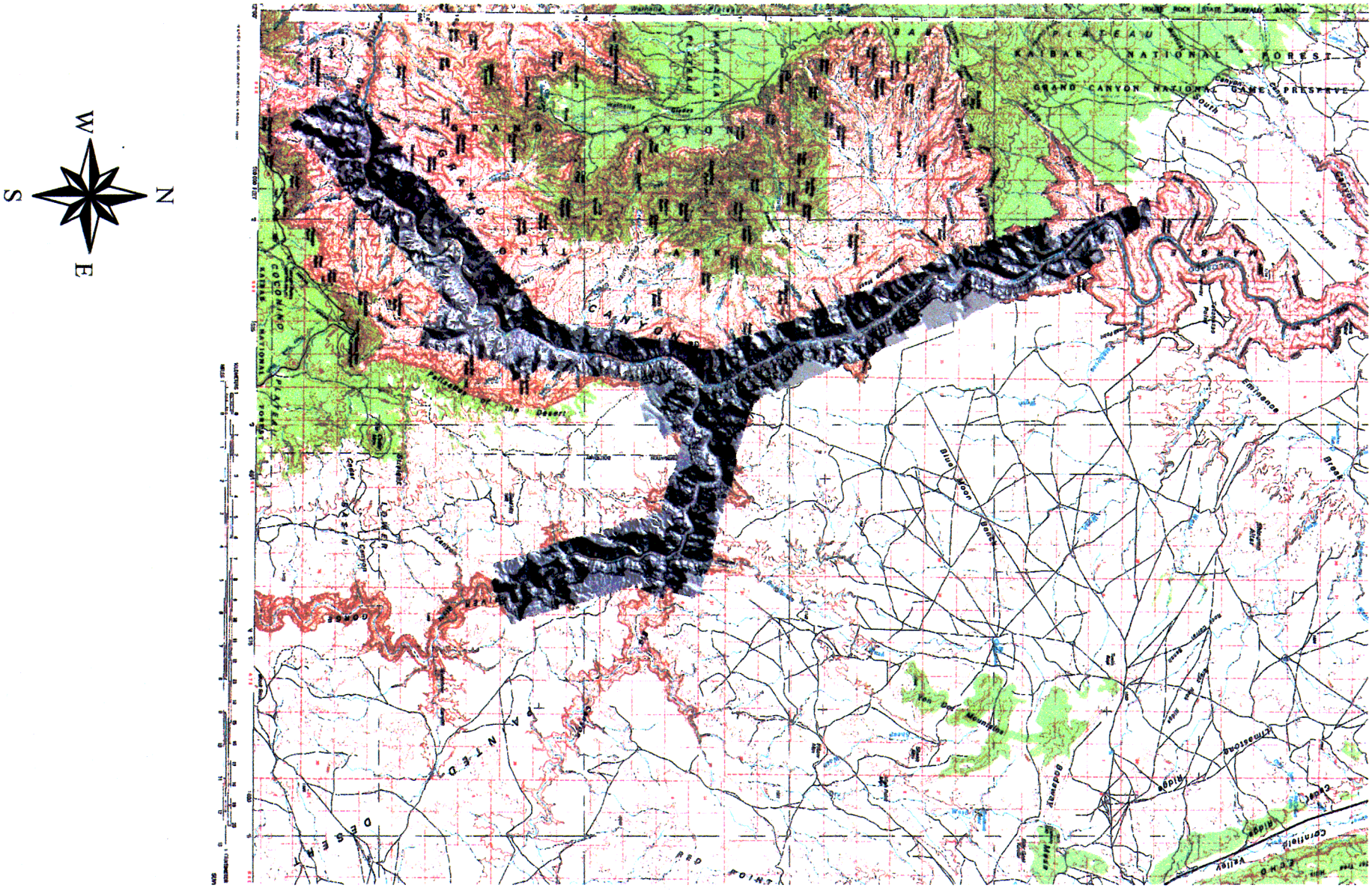
1% of Data Collected Displayed

Reference Exhibit Only

Grand Canyon
LIDAR Scan Coverage

Date: June 17, 2000

Exhibit : #2



EARTHDATA AVIATION

18227 AIRPARK DRIVE-HAGERSTOWN-MARYLAND-21742

EarthData Job Number: EA 00145

Flight Date: March 27, 2000

UTM Zone 12

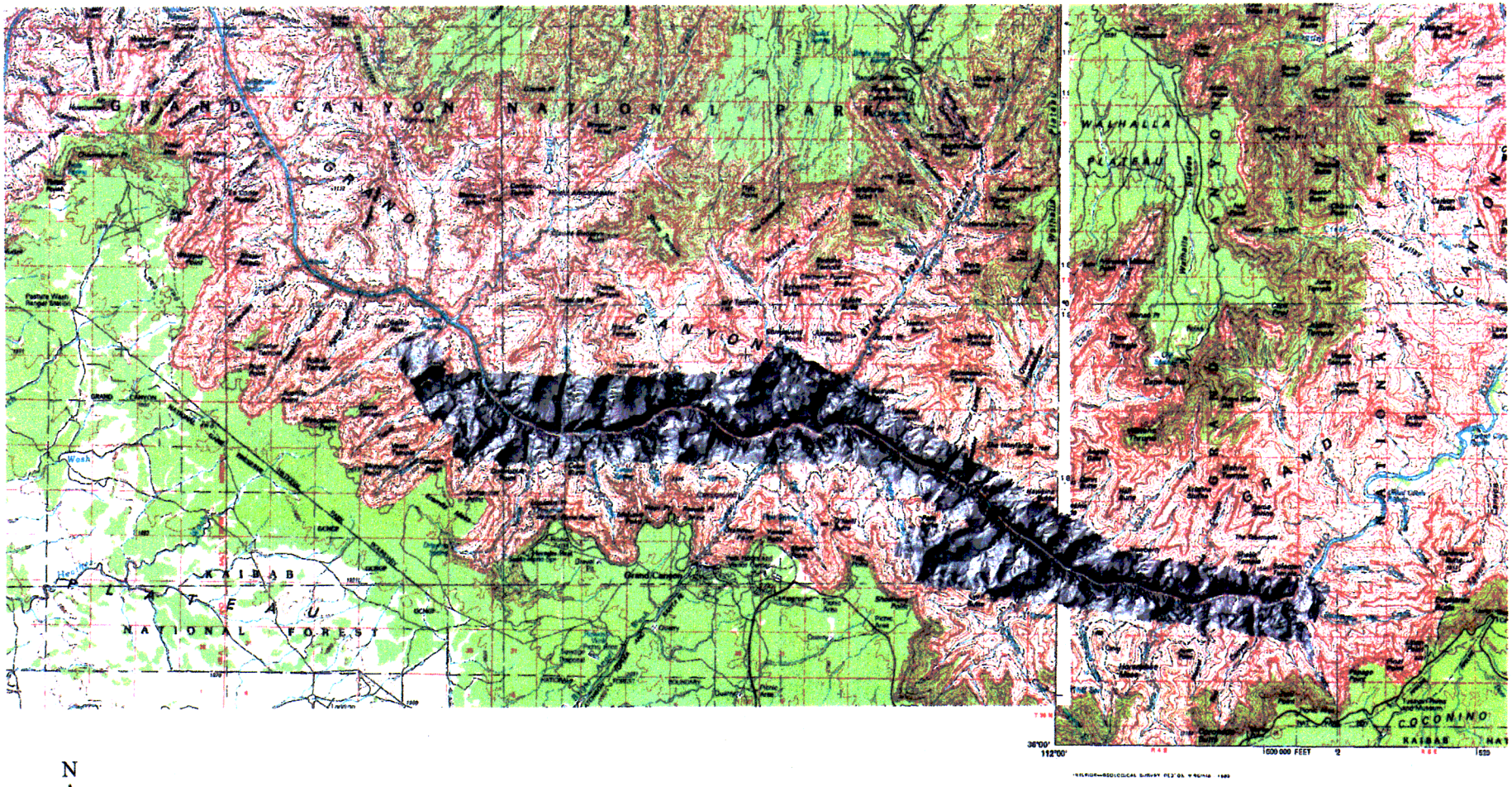
1% of Data Collected Displayed

Reference Exhibit Only

Grand Canyon LIDAR Scan Coverage

Date: June 17, 2000

Exhibit : #3



N
W E
S

EARTHDATA AVIATION

18227 AIRPARK DRIVE-HAGERSTOWN-MARYLAND-21742

EarthData Job Number: EA 00145

Flight Date: March 27, 2000

UTM Zone 12

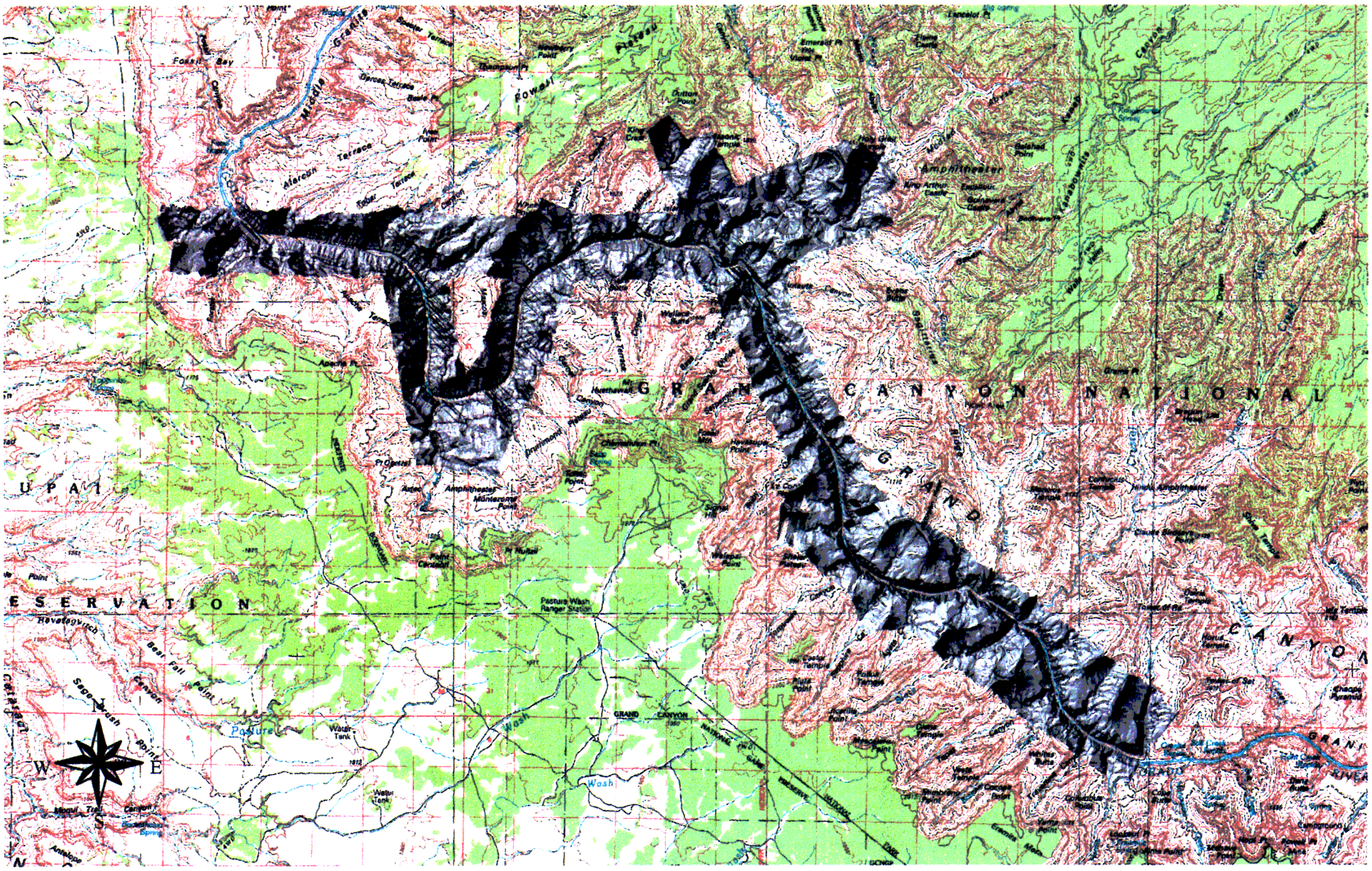
1% of Data Collected Displayed

Reference Exhibit Only

Grand Canyon LIDAR Scan Coverage

Date: June 17, 2000

Exhibit: # 4



EARTHDATA AVIATION

49027 AIRPARK DRIVE HAGERSTOWN MARYLAND 21742

EarthData Job Number: EA 00145

Flight Date: March 27, 2000

UTM Zone 12

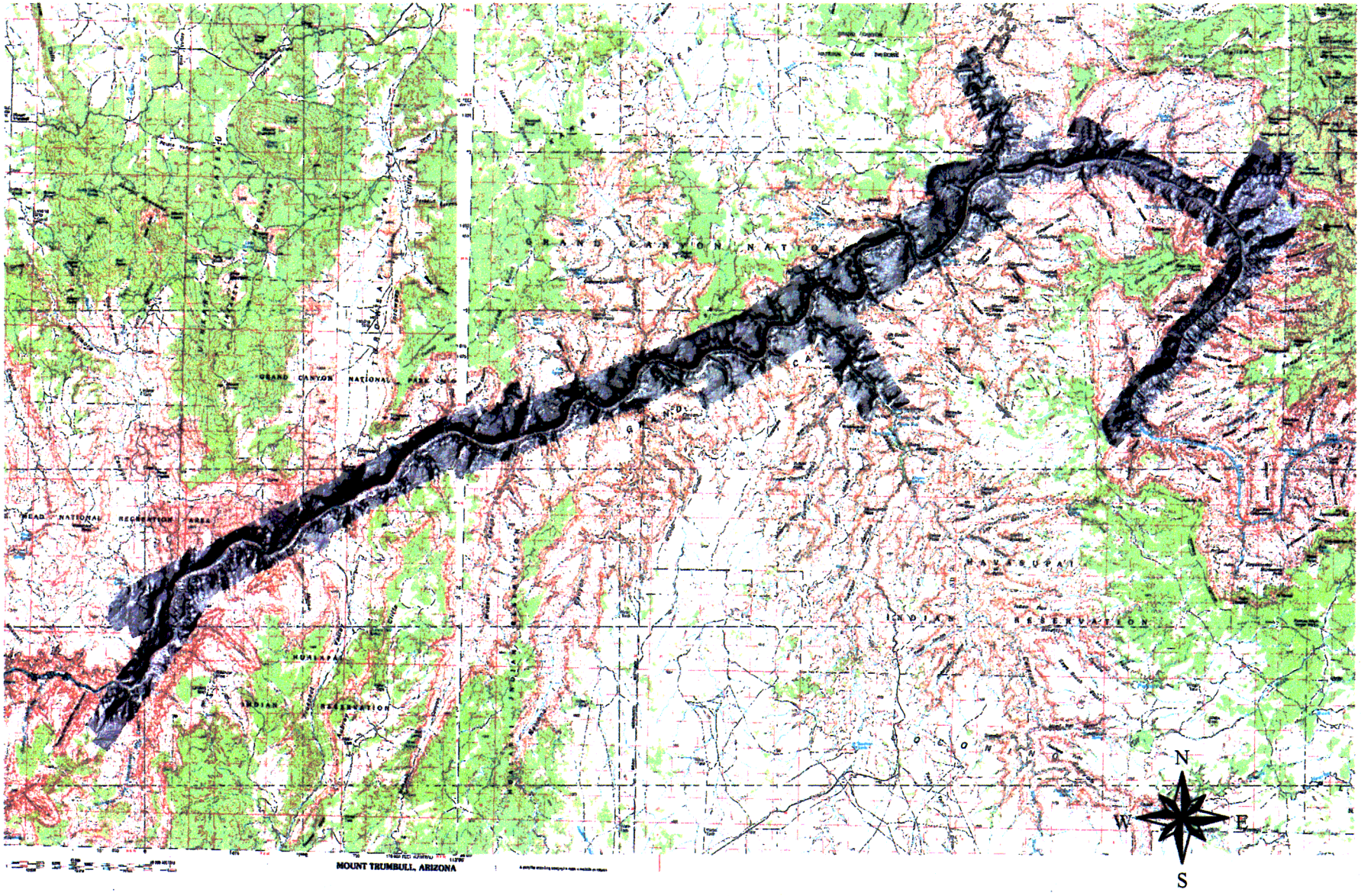
1% of Data Collected Displayed

Reference Exhibit Only

Grand Canyon LIDAR Scan Coverage

Date: June 17, 2000

Exhibit: # 5



EARTHDATA AVIATION

18227 AIRPARK DRIVE-HAGERSTOWN-MARYLAND-21742

EarthData Job Number: EA 00145

Flight Date: March 27, 2000

UTM Zone 12

1% of Data Collected Displayed

Reference Exhibit Only

Grand Canyon LIDAR Scan Coverage

Date: June 17, 2000

Exhibit: # 6

N
W E
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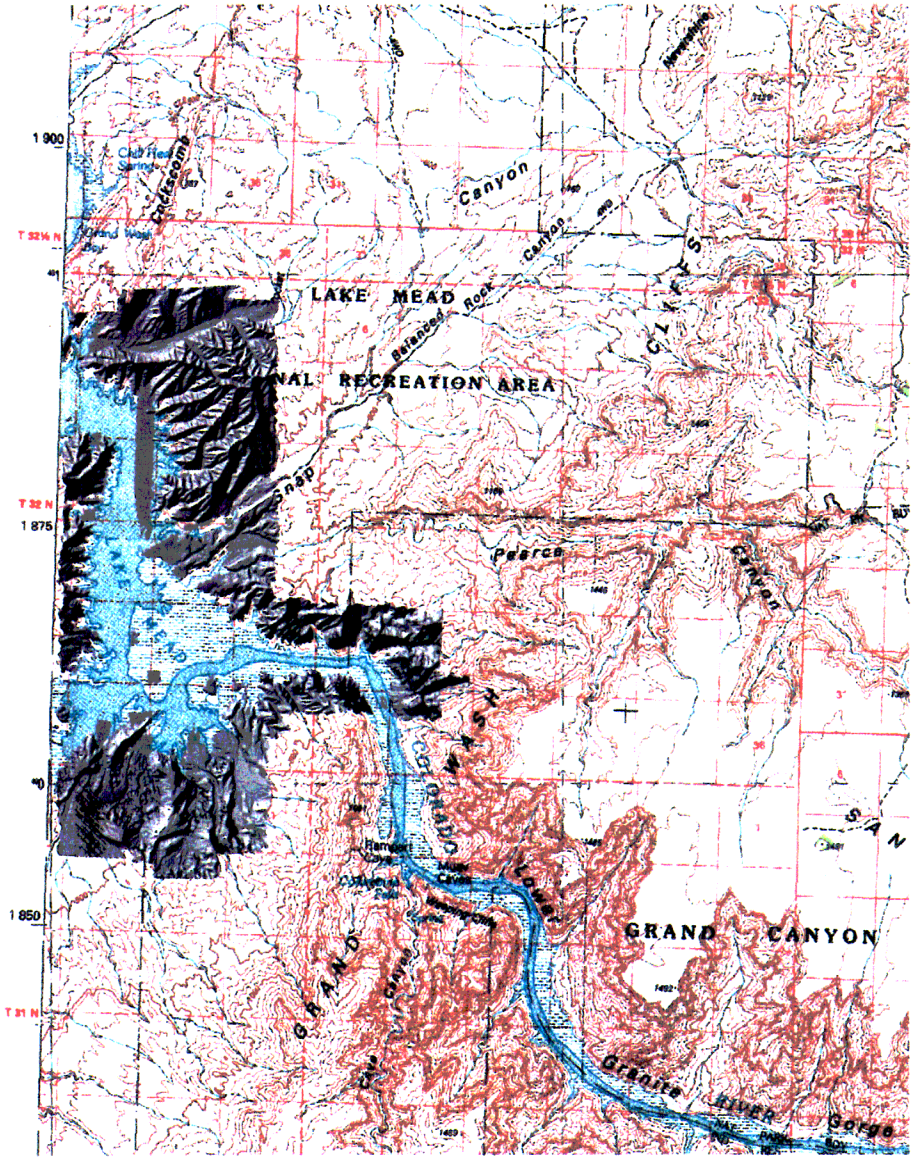
EARTHDATA
AVIATION

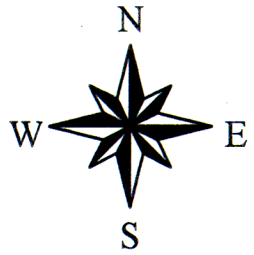
18227 AIRPARK DRIVE-HAGERSTOWN-MARYLAND-21742

EarthData Job Number: EA 00145	
Flight Date: March 27, 2000	
UTM Zone 12	
1% of Data Collected Displayed	
Reference Exhibit Only	

Grand Canyon LIDAR Scan Coverage

Date: June 17, 2000	Exhibit: # 7





EARTHDATA AVIATION

18227 AIRPARK DRIVE-HAGERSTOWN-MARYLAND-21742

EarthData Job Number: EA 00145

Flight Date: March 29, 2000

UTM Zone 12

1% of Data Collected Displayed

Reference Exhibit Only

Grand Canyon LIDAR Scan Coverage

Date: June 17, 2000

Exhibit: # 8