FUGRO LADS, INCORPORATED

Report of Survey

DATA VERIFICATION REPORT

LAKE SUPERIOR BATHYMETRIC LIDAR

COASTAL SERVICES CENTER

NATIONAL OCEANIC SERVICE

NATIONAL OCEAN AND ATMOSPHERIC ADMINISTRATION

U.S. DEPARTMENT OF COMMERCE

CONTRACT EA133C-05-CQ-1051

FEBRUARY 11, 2011

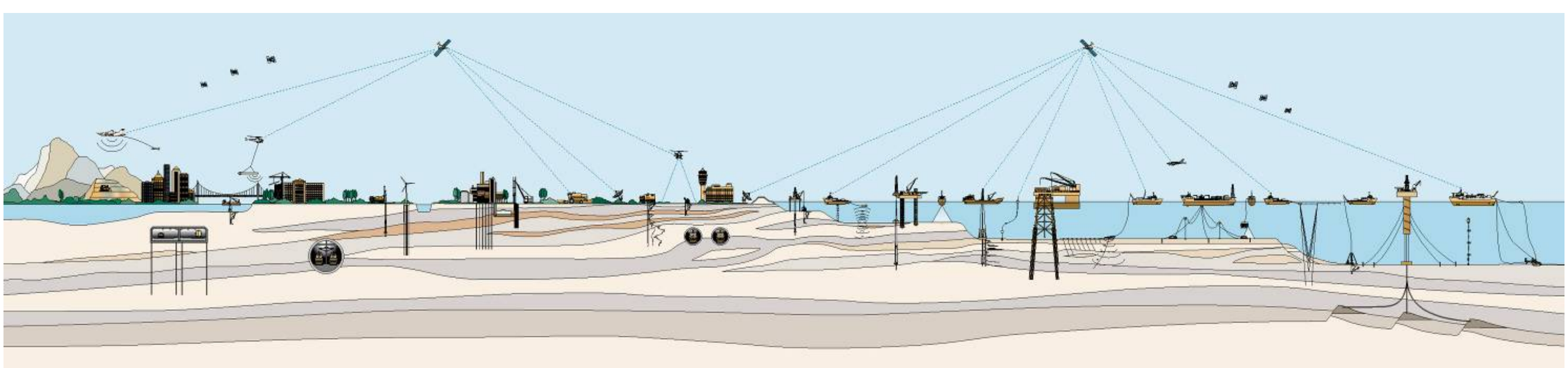

TABLE OF CONTENTS

1 DATA ACQUISITION

1.1 LADS Mk II Overview

The LADS Mk II is a shallow water hydrographic LIDAR survey system that has been designed and developed by Fugro LADS. The LADS Mk II system comprises the Airborne System (AS) permanently fitted to a specially modified Fokker F27 aircraft, and a proprietary Ground System GS.

Figure 1 - The LADS Aircraft – Fokker F27 (VH-EWP)

1.1.1 LADS Mk II Airborne System

The AS is capable of detecting submerged objects measuring 2x2x1m and is capable of measuring water depths to 70m. Data collection with the LADS Mk II AS is characterized by:

- **Swath width independent of operating height makes for efficient survey line planning and execution. In particular, this reduces the effect of low cloud and high terrain on survey productivity.**
- **Interface with the aircraft autopilot to ensure accurate track keeping, which in turn minimizes data gaps and promotes efficiency in per-sortie productivity.**
- **Rectilinear scan pattern provides for high accuracy mean sea surface calculation.**
- **Topographic capability relative to the survey datum.**
- **Stabilized platform to ensure LIDAR sounding position in turbulent conditions, removing the potential for gaps and reflies.**
- **High laser power (7mJ per pulse), high efficiency optics and large dynamic range receiver system, including AGC and PMT.**

Upgrades to the system planned for 2010 included the incorporation of a Hyperspectral sensor into the AS and improvements in the relative reflectance algorithms.

The current operating specifications for the LADS Mk II system are shown in the table below:

Aircraft Type:	**Fokker F-27**
Aircraft Endurance	**7 – 7.5 hours (average)**
Aircraft Range	**up to 1500 nautical miles**
Aircraft Transit Speed	**220 knots**
Aircraft Transit Altitude	**18,000 to 23,000ft (fully pressurized)**
Aircraft Survey Line	**< 3m 1SD via autopilot coupling**
Survey Configuration	**altitude 1200 to 2200 ft, speed 140 to 175 kts**
Airborne System	**– stabilized optical platform (for accurate angular measurements) with ring laser gyro AHRS – single operator console – two equipment cabinets**
Operational Capability	**full day or night operation, all weather (VFR, IFR) tailwind <50**
Airborne Survey Crew	**1 operator, 1 flight coordinator**
Depth Sounding Rate	**900 soundings per second, 3.24 million soundings per hour**
Depth Range	**to 70 m dependent on water clarity**
Topographic Range	**to 50 m above sea level**
Sounding Density	**2 x 2 m, 2.5 x 2.5 m, 3 x 3 m, 4 x 4 m and 5 x 5 m**
Swath Width	**independent of operating height and water depth 240 m at 5 x 5 m, 175 kts, 100 m at 3 x 3m, 150 kts**
Digital Imagery Capability	**Redlake MegaPlus II ES 2020 digital camera**
Scan Pattern	**Rectilinear**
Position Systems	**Real-time WADGPS and post-processed KGPS**
Horizontal Accuracy	**IHO SP44 5th Edition, February 2008 Order 1**
Vertical Accuracy	**IHO SP44 5th Edition, February 2008 Order 1**
Object Detection	**2x2x1m object 95% confidence @ 3x3m x 200% or 2.5x2.5 @ 100%**
Area Coverage	**65 km^2 per hour, 5 x 5m 20% overlapped 22 km^2 per hour, 3 x 3m 25% overlapped**
Raw Data	**Digital Linear Tape (DLT)**
Ground System	**Fully transportable system for planning, data processing and review**
Ground Processing Time	**< 0.5:1 compared with acquisition time**

Table 1 – Operating Specification for the LADS Mk II System

LADS Mk II soundings are acquired by the transmission of laser pulses from the aircraft through a scanning system and detecting return signals from land, the sea surface, the water column and the seabed. The transmitting and receiving components are housed on a stabilized platform that compensates for aircraft pitch and roll. The return signals are electronically amplified and conditioned prior to being digitized and logged.

In the aircraft a laser, scanner, optical system, PMT and conditioning electronics collect the raw sounding signal. Aircraft position information is obtained from the Global Positioning System (GPS). Three computers, linked via an FDDI optic fiber network, control and monitor the AS operations as shown in the diagram below.

Prior to a sortie, planning information is passed from the GS to the AS. During the sortie, logged raw sounding, position and AS data is logged on tape and hard disk, which is later processed on the GS at the completion of the sortie.

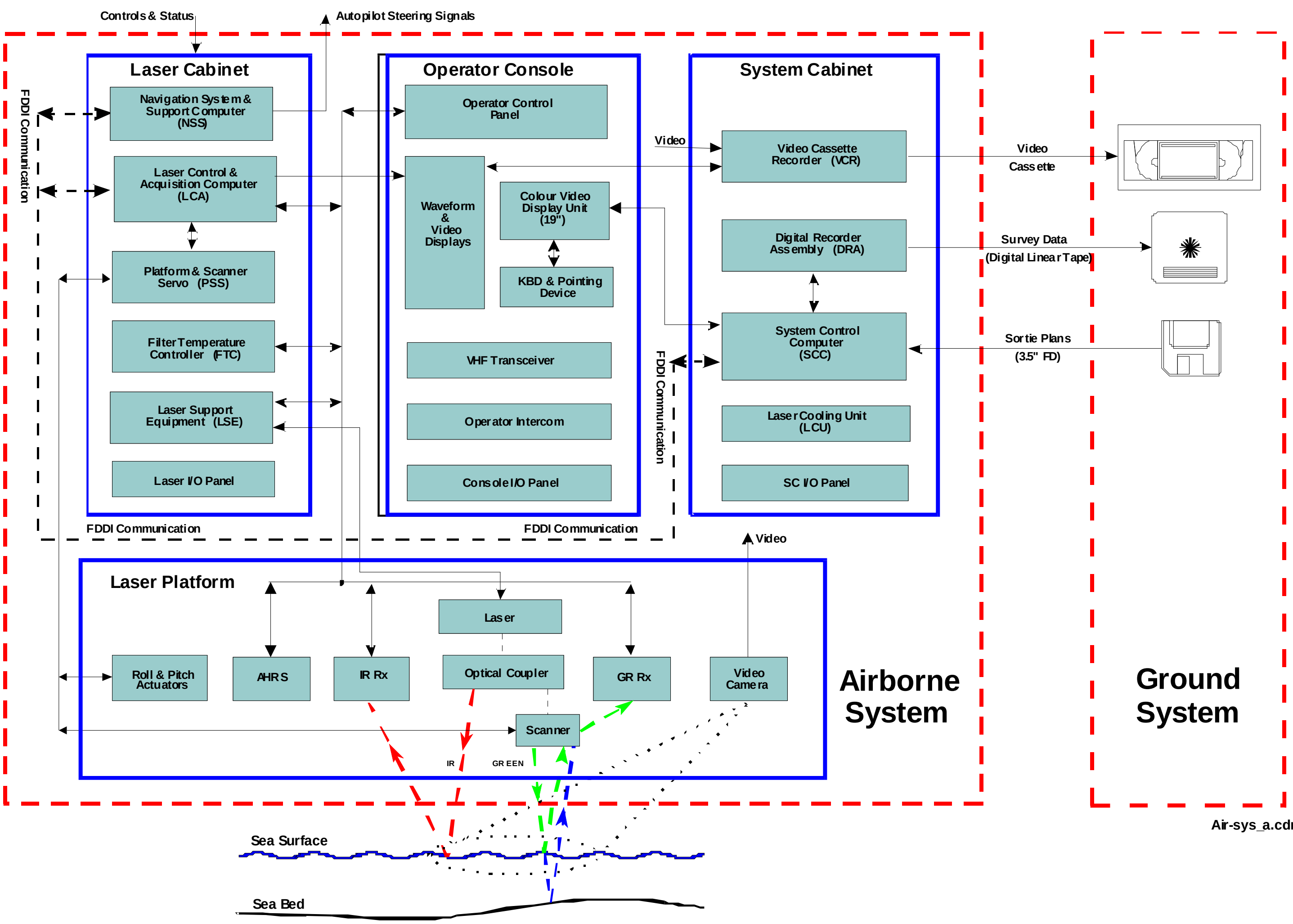

Figure 2 – LADS Mk II Air System

The LADS Mk II system is designed to collect the highest quality data in the widest range of environmental conditions. This is important because no amount of data processing can turn poor quality data into good data. An essential feature of the LADS Mk II system is the collection of high amplitude, low noise waveforms.

High laser power directly influences the depth detection capability of LIDAR systems far more significantly than the laser sounding rate.

High laser power, while retaining eye safe laser operation, is a fundamental tenet of the LADS Mk II system design.

1.1.2 LADS Mk II Dedicated Aircraft

The Fokker F27 has proven itself as a reliable bathymetric LIDAR platform in operating for the AHS LADS survey program from 1991 until September 2009. From November 2009 it was fitted and operated with the new RAN LADS II system. The RAN LADS II AS and LADS Mk II AS are functionally the same, and the Fokker has operated effectively during this period. This demonstrates the compatibility of the Fokker with the LADS Mk II AS.

The primary features and capabilities of the Fokker F27 are:

- The aircraft is owned by Fugro.
- It is registered in Australia and complies with applicable United States Federal Aviation Authority (FAA) and ICAO regulations and other applicable state and federal regulations.
- Permanent installation of the AS reduces the risk of system calibration problems occurring during mobilization that can delay project startup or impact upon data accuracy.
- The large aircraft, fitted with long-range tanks, provides over 7-hours endurance for the LADS aircraft. This facilitates rapid global transits, transits between alternative distant survey areas, and high per-sortie productivity; this is especially evident in areas with frequent inclement weather, when good-weather days can be maximized.
- The larger aircraft can operate in a wider environmental envelope, and is less susceptible to wind and turbulence.

1.1.3 LADS Mk II Ground System

The primary functions of the Ground System (GS) are:

- Mission planning. This includes the specification of the total survey area, spheroid and grid data, survey sub-areas, line spacing, swath widths, survey lines to cover the sub-areas, individual survey lines, crosslines, tidal areas and navigation check points. At the commencement of a survey, one or more databases are established on the GS. Each database contains spheroid and grid data, tide data and survey objectives. Sub-areas are defined, covering the specific areas to be surveyed. Survey lines are then generated for each sub-area at an operator-specified line spacing. Entering start and end coordinates can specify other survey lines.

- Sortie planning. A sortie plan is the specification of a series of survey objectives to be executed by the AS. Prior to each sortie, survey objectives are selected from the appropriate database and written to floppy disk along with grid and spheroidal information. This plan is read by the AS and used to control sortie operations.
- Sortie automatic data processing. This function calculates sounding depths and positions from the raw sounding data logged by the AS. Depths and positions are associated with various confidence metrics. Processing parameters suitable for the sortie are set prior to processing. Tides may be either observed or predicted and can be reapplied at any time. Relative Reflectance is also calculated. On completion of automatic line processing operator validation, checking and approval of the sounding data can be conducted.
- Data pre-validation review, validation, checking and approval. Surveyors validate the calculated soundings, editing soundings as appropriate. The validated data is checked by a more senior surveyor and finally approved by the Field Party Leader.
- Data output. Approved data is output for the client in digital form.

A recent LADS enhancement is a new GS called *hydra,* which features increased portability, efficiency and expandability. *Hydra* maintains the full software functionality of the previous server-based GS with the following improvements:

- Mission Planning Aids. A number of minor additions have been provided to assist in mission planning activities. These include the ability to import run line definitions from CSV files, provision for text descriptions of run and sub-areas, and an option for automatic specification of run swath-width and spacing based on density and overlap parameters.
- Mission Area Window. This feature provides a 2D graphical view of the area to be surveyed. A georeferenced chart image can be imported for reference. Runs and sub-areas can be created interactively and overlaid upon the chart image to aid the planning process.
- Total Propagated Error. Total propagated error can now be estimated for each sounding. This feature takes into account aspects such as GPS accuracy, sea state and water clarity. Note that TPE estimation relies upon manual sampling of sea state and water clarity at the time and location of data collection.
- Fledermaus Integration. The GS has been integrated with the third party GIS tool 'Fledermaus' from IVS. This feature allows an area of sounding data to be exported to Fledermaus interactively via the Mission Planning Window. The data can then be visualized within the Fledermaus Application. The GS Waveform and Image displays are automatically synchronized to the sounding nominated within Fledermaus. Soundings selected or rejected from Fledermaus are automatically reflected within the GS database.
- Mission Progress Reporting. A report is now available that provides a statistical summary of mission progress.

As a result of this change, the operating system has changed from UNIX to Linux.

In addition, *hydra* provides facilities for the generation of survey management plots and reports. It also contains peripheral devices for printing, plotting, generating sortie plans, reading raw data from the AS and GPS reference stations and accessing media for backups of the database.

1.2 Fugro LADS Software

A list of Fugro LADS software used on the GLRI survey is depicted in the table below:

System	Version	Remarks
Fugro LADS GS	L.3.3	LADS MkII Ground System Software
Fugro LADS AS	AS 9.0.5	LADS MkII Airborne System Software
GPS Logging AS	3.22	GrafNav GPS Data Logger Software
Dynamic GPS Processing	8.10	GrafNav (Precise Differential GPS Navigation Trajectory Software)
Static GPS Processing	8.10	GrafNet (Precise Differential GPS Stationary Software)
CARIS BASE Editor	2.3	Chart Compilation Software
CARIS HIPS and SIPS	7.0.2	Bathymetric Data Processing Software
MBT	–	LADS Mk II Mosaic Build Tool
Global Mapper	11.02	Image Compression Software
ArcGIS	9.3.1	Product Compilation Software
Fugro Workbench	4.1.8	Product Compilation Software

Table 2 – Current Operating Systems

1.3 Project Design

This project was designed around a plan to fly 16.75 flights, at 3 fully effective sorties per week, of 6.5 hour duration. With a day for mobilization and de-mobilization, this plan equated to a total of 41 days to conduct the airborne component of the project. Transit times were to be kept to a minimum by utilizing Duluth International Airport for the western survey areas and Sawyer International Airport for the eastern areas. The main base of operations was to be Duluth. A total of 3 separate forward deployments of the flight crew to

Sawyer, for ~4 days at a time, were factored into the project design. In order to avoid a temporary suspension of operations, one of the forward deployments to Sawyer was scheduled to coincide with the Duluth International Air Show between the 15th and 18th of July.

An allowance was made for weather and aircraft holding (10% of flight time) and the performance of the following in-flight QC checks:

- crosslines (5% of flight time)
- navigation position checks and depth benchmark comparisons on every 2nd flight (4% of flight time)

A refly rate of 10% of the flight time was adopted. In practical terms, this meant that gaps due to poor water clarity (turbidity) were to be reflown in an attempt to fill the gap on one additional occasion only.
In order to meet the required survey point density and accuracy specifications for this project, the parameters for data capture were:

Shoreline (km)	Number of Lines	Total Line Nmi	Min % of Sidelap	Altitude (ft)	Speed (kts)	Pulse Rate (Hz)	Scan Rate (Hz)
~720	435	5162	12.5% *	1200-2200	175	900	18

Swath Width (m)	Line Spacing (m)	Average Point Density (m)
240	210	5

** The LADS Mk II navigation system is integrated with the aircraft Autopilot, ensuring there are no gaps between survey lines.*

Table 3 – Data Acquisition Parameters

1.3.1 Initial Survey Area

In the figure below, the sub areas required to cover the NOAA priority project area are shown in red. The additional coverage that was to be acquired along the western shoreline of Lake Superior is indicated by blue polygons. The sub-areas illustrated in Figure 3 were to require 16.75 sorties to complete with the LADS Mk II system.

The initial survey area was separated into 3 individual data collection areas. This was necessary as the entire initial survey area was very large and was not confined to one UTM zone. Although data is collected using GPS geographic coordinates, all mission planning is performed using grid coordinates. Therefore, if points exist significantly outside of the UTM zone used for mission planning, errors in position can be introduced. In addition, separate databases were created for each individual data collection area so that if data collection was completed in one database earlier than the others, then that specific database could be sent back to the main office in Mississippi for data processing. This removed some of the dependence on the number of surveyors in the field, thereby reducing cost.

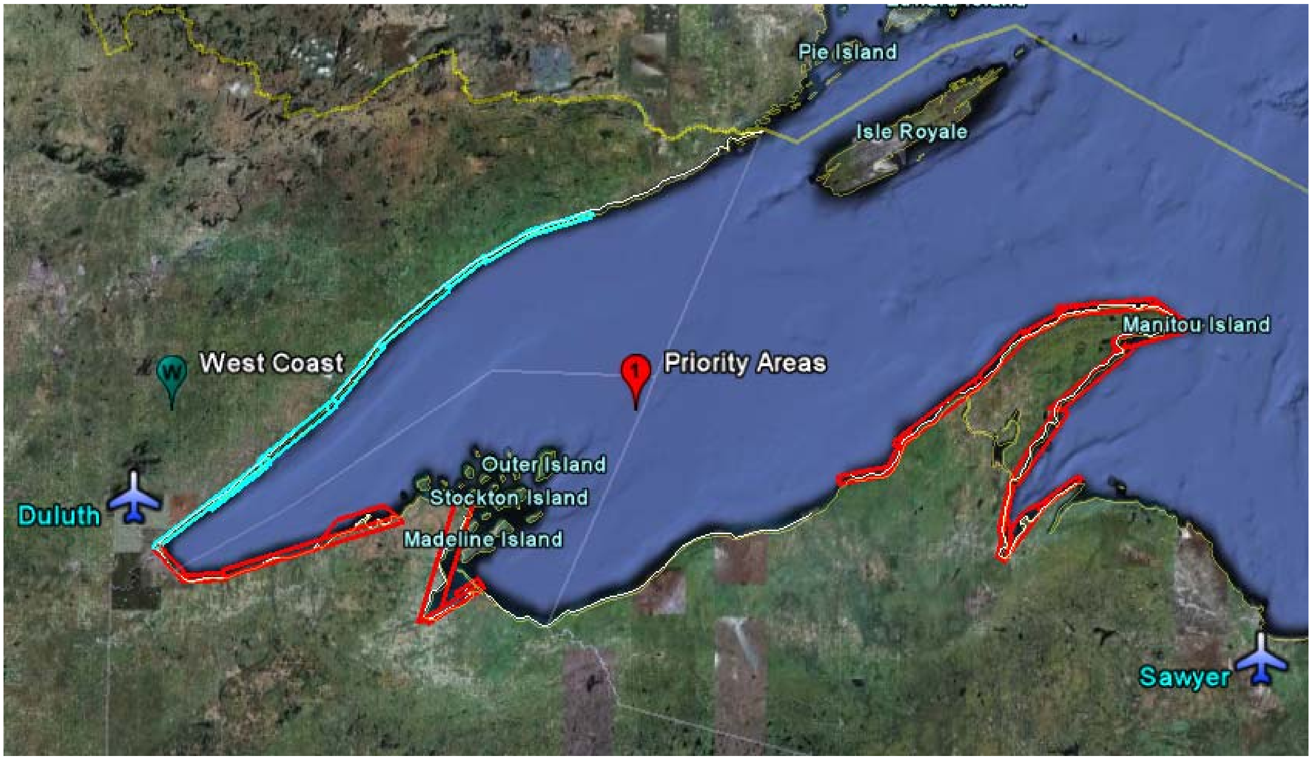

Figure 3 – Priority Areas (red polygons) and West Coast of Lake Superior (blue polygons)

1.3.2 Final Survey Area

During the kick off meeting prior to data collection an agreement was made that, instead of flying off shore lines beyond extinction depth within 1 km of the shore line, additional sub areas would be collected to the north of planned coverage along the west coast of Lake Superior. In Figure 4 below, these additional areas are seen extending close to the US/Canadian boarder.

Some sub areas were substituted due to water clarity conditions South of Duluth, MN and North of Ashland, WI making data collection unsuccessful. These sub areas can also be seen in Figure 4. The first substitution moved an area southwest of Duluth, MN in Area 1 to an area east of Area 3. The second substitution replaced the area north of Ashland, WI in Area 2 to an area from the Michigan border to the Ontonagon River.

A final addition to Area 3 was introduced after an additional $10,000 was made available; this extended Area 3 to the east, creating a small sub area of 10 lines approximately 12 kilometers long.

More information on the survey extension and substitutions can be found in section 1.5.1.

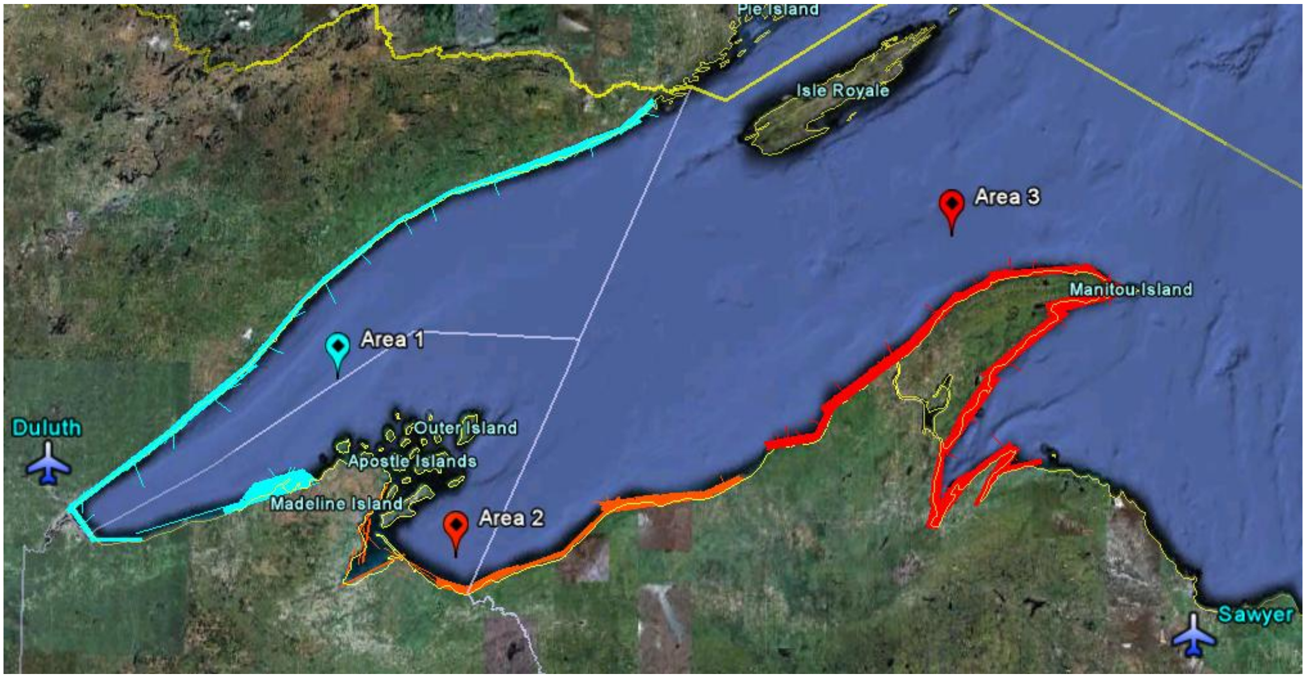

Figure 4 – Final Survey Areas and Flight Lines

Project Area	Budgeted Effective Flights	Equivalent Effective Flights Flown	Budgeted Flight Lines	Flight Lines Flown	Budgeted Length of Flight Lines (km)	Length of Flight Lines Flown (km)	Budgeted Length of Shoreline (km)	Length of Shoreline Acquired (km)
Area 1	6	7.25	135	226	3,580	5,928	310	370
Area 2	2.7	3.25	70	107	1,070	2,202	90	110
Area 3	8.3	10.5	230	342	4,910	6,984	320	420
Total	17	21	435	675	9,560	15,114	~720	~900

Table 4 – Planned Survey Requirements and Final Survey Achievement

1.4 Environmental Conditions

1.4.1 Lake Surface Conditions – Sea State, White Water, Swell

Due to Lake Superior's size, some wind-driven surface conditions existed; the sea state varied from 0 – 2 depending on wind strength and direction. There was not any significant swell in any part of the survey area. During periods of strong winds and rough seas some white water existed around drying features. This was very rare.

Calm lake surfaces were experienced on occasions. Under such calm conditions the lake surface became glassy in protected areas, which degraded the sea surface model and resulted in some shallow water gaps at nadir, where the sea surface returns were completely saturated and seabed returns attenuated. These situations occurred mostly in protected bays along the western coast of the lake. During very calm conditions these areas were avoided, other areas were surveyed and the glassy areas were surveyed in more suitable conditions on subsequent flights. In the event of gaps, lines were reflown at a different date or additional offset lines were created to complete the coverage utilizing outer scans of the flight line.

1.4.2 Water Clarity

The water clarity in the survey area varied significantly depending on the geographic nature of the coastline. River runoff created areas of turbidity during and after periods of heavy rain. When possible, areas of known river runoff were avoided for a number of days following a rain storm before attempting data collection again. Daily monitoring of river discharge increased the chances of successful data collection in these areas. Some gaps remained in the data where river runoff was constant; these gaps were minimized as much as possible. Water clarity varied from extremely poor to good.

1.4.3 Topography

The LADS Mk II system can measure topographic heights up to 50m in elevation, subject to the depth / topographic logging window selected. For this survey, a 50m topographic height logging window was selected. As a result, the coastline was surveyed to achieve coastline coverage to 30m beyond the shore line. First return elevations were measured above 30m in areas where the coastline rose sharply or large trees grew close to the shore line.

1.4.4 High Ground

For this survey high ground was not an issue. Around the Duluth area, however, some radio towers exist. Survey lines were planned carefully to avoid flying close to these areas.

1.4.5 Wind

Survey operations were conducted in wind strengths of up to 25kts during the survey. In general, the wind strength during sorties was between 5 and 15kts. In certain areas, wind strengths above 20kts generated turbulence that made data collection difficult. In circumstances where wind speeds were forecast to be greater than 20kts, no sorties were planned due to the possibility of dangerous levels of turbulence.

1.4.6 Cloud

Low cloud coverage and rain were not significant in survey operations. Some low cloud existed locally when rain storms were present. Therefore, when the cloud base dropped below 1200ft, operations were diverted to other survey areas. Weather was monitored daily to ensure that the conditions were appropriate for data collection. If weather conditions were unsuitable, no flights were attempted and data processing continued in the survey office.

1.5 Project Timeline

Below is the project time table for major events in data collection, processing and final delivery of the Lake Superior data.

June 27th 2010	Aircraft arrival at Duluth International Airport
June 28th 2010	Mobilization of aircraft and remote processing office
June 29th 2010	Kick off meeting at Fugro EarthData, Inc. In Attendance: Dennis Hall (NOAA CSC) Lindy Betzhold (NOAA CSC) Keil Schmid (NOAA CSC) David Scharf (NOAA OCS) Chris Macon (JALBTCX) Steve Raber (Photo Science) Kurt Allen (Photo Science) Carol Lockhart (Geomatics Data Solutions) Ed Saade (FEDI) Dave White (FEDI) Richard McClellan (FEDI) Becky Jordan (FEDI) Scott Ramsay (FLI) James Guilford (FLI) David Millar (FPI)
June 29th 2010	Extension of offshore lines beyond extinction depth transferred to additional coastline coverage north of Area 1 determined during kick off meeting. See section 1.5.2 below
June 29th 2010	Aircraft on Ground (AOG) due to aircraft inverter failure
July 2nd 2010	First Flight – system and aircraft operated well
July 15th-19th 2010	Forward deployment to Sawyer, MI
July 29th 2010	Substitution of poor Lidar areas for better areas. Area south west of Duluth substituted for area east of Keweenaw Peninsula and area north of Ashland substituted for area east from Wisconsin/Michigan boarder. See section 1.5.1 below
August 6th 2010	$10,000 extension to eastern extents of survey area. See section 1.5.1 below
August 12th 2010	Final Flight
August 13th 2010	Demobilization
August 16th 2010	Aircraft departure
October 15th 2010	Pilot tiles delivered

November 8th 2010	Independent QC of pilot tile data received from Geomatics Solutions.
November 17th-18th 2010	Pilot tile QC meeting held at Fugro LADS Office In Attendance: Keil Schmid (NOAA CSC) Carol Lockhart (Geomatics Data Solutions) Richard McClellan (FEDI) James Guilford (FLI) Michael Hawkins (FLI) Brett Weidman (FLI)
November 17th 2010	Pilot tile resubmission date set for December 31st 2010 during Pilot tile QC meeting
December 27th 2010	Pilot tile resubmission
December 29th 2010	Data processing completed
February 11th 2011	Final data delivered to NOAA CSC

Table 5 – Specific Dates of Project

The majority of flights commenced in the mid- to late-afternoon to optimize low sun angles and peak surface wind conditions. On occasion, sorties were conducted earlier in the day if weather was forecast to deteriorate, or later if waiting for weather to improve. All flights were completed no later than shortly after sunset, as low-safe altitude night restrictions existed across Lake Superior in close proximity to the shoreline.

The pertinent information regarding each specific sortie is detailed in the table below:

Date (2010)	JD (2010)	Project Sortie Number	Start Time (Local)	End Time (Local)	Sortie Duration	Time on Task	Airport of Departure
July 2	183	1	15:36	21:50	6:14	4:26	Duluth
July 3	184	2	14:00	20:23	6:23	5:16	Duluth
July 5	186	3	16:02	19:24	3:22	1:10	Duluth
July 6	187	4	15:52	21:23	5:31	4:23	Duluth
July 8	189	5	15:29	21:56	6:27	5:08	Duluth
July 9	190	6	15:20	21:50	6:30	5:27	Duluth
July 10	191	7	16:26	21:31	5:05	4:14	Duluth
July 12	193	8	15:20	22:02	6:42	5:05	Duluth
July 13	194	9	15:35	21:50	6:15	5:20	Duluth
July 15	196	10	15:41	21:52	6:11	5:06	Duluth
July 16	197	11	16:34	22:42	6:08	5:17	Sawyer
July 17	198	12	15:23	21:35	6:12	5:05	Sawyer
July 19	200	13	14:34	21:21	6:47	5:06	Sawyer

July 23	204	14	16:58	21:29	4:31	3:40	Duluth
July 25	206	15	15:01	21:42	6:41	5:28	Duluth
July 26	207	16	15:28	20:20	4:52	3:30	Duluth
July 28	209	17	15:38	21:52	6:14	5:09	Duluth
July 29	210	18	14:38	21:00	6:22	4:32	Duluth
July 30	211	19	14:43	20:29	5:46	3:40	Duluth
August 1	213	20	13:33	19:59	6:26	4:47	Duluth
August 3	215	21	15:00	21:19	6:19	5:10	Duluth
August 4	216	22	14:17	20:21	6:04	3:44	Duluth
August 6	218	23	14:32	21:36	7:04	5:27	Duluth
August 7	219	24	14:42	20:33	5:51	4:01	Duluth
August 9	221	25	13:14	19:00	5:46	2:41	Duluth
August 12	224	26	12:30	19:21	6:51	5:46	Duluth
				Total	156:34	118:38	
				Mean	6:01	4:33	

Table 6 – Specific Dates of Data Acquisition

1.5.1 Area Extensions and Substitutions

During the course of the survey, communications between the customer and the client indicated a desire to achieve the most value for money spent. This translated to two extensions and two area substitutions.

The first extension was to continue data collection to the north of area 1, utilizing survey lines that existed beyond extinction depth that would not be required for flight. Due to the steep nature of the lake bottom along the western coast and around the Keweenaw Peninsula, as many as 3 planned lines from several sub-areas were not required. These lines were transferred to the north of area 1, resulting in an additional 60km of linear coastline coverage. This coverage can be seen in Figure 5.

Figure 5 – Data Coverage due to Substitution of Offshore Lines for Additional Coastline

The second extension came from an additional $10,000 in funding. This extension continued the data coverage to the east of the area 3 survey area. The additional funding added approximately 10km of linear coastline coverage. This coverage can be seen in Figure 6.

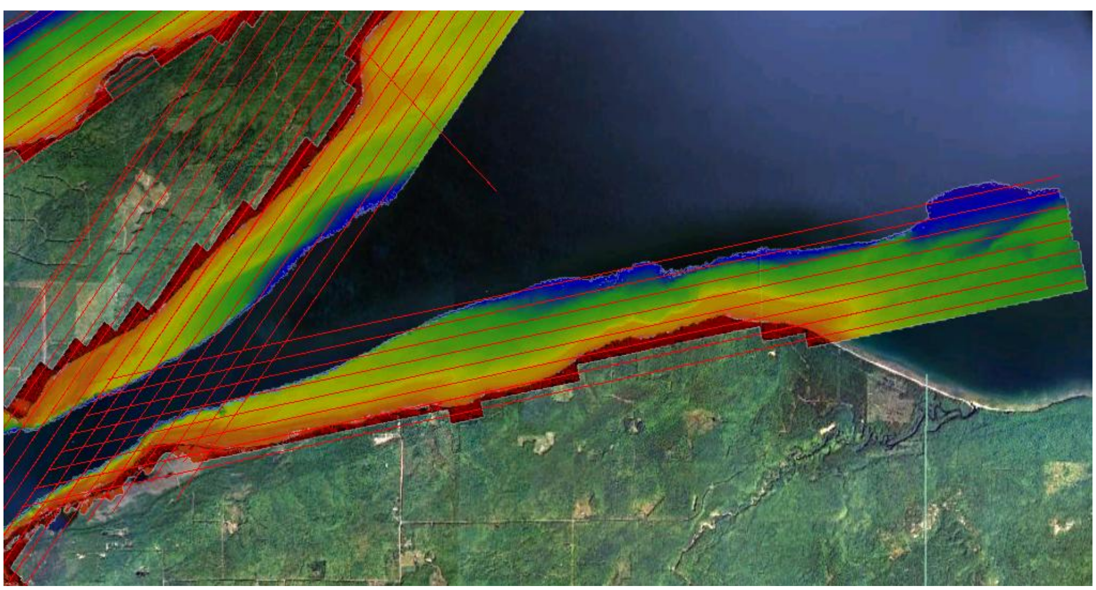

Figure 6 – Additional Coverage East of Area 3

The first substitution was proposed to move subareas southwest of Duluth, MN to the east of the Keweenaw Peninsula, east of the proposed area 3 data collection areas. This substitution was proposed due to significant river runoff from the St. Louis River and the natural currents in the lake. Large quantities of suspended sediment existed from the mouth of the river east along the Wisconsin coastline, making survey operations unsuccessful. A total of 6 flight lines were flown through this area as well as visual checks of the area while transiting. These checks confirmed that the water clarity in this area would remain poor for the duration of the survey.

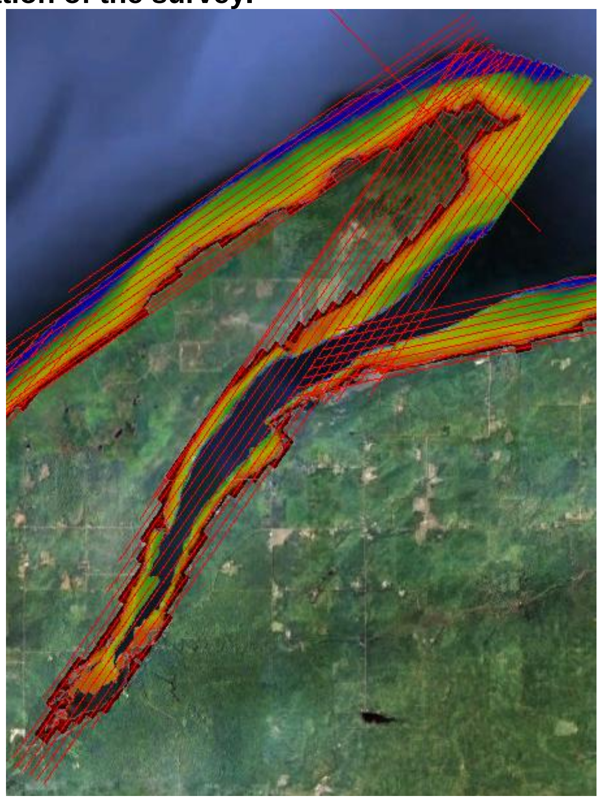

Figure 7 – Area 3 Substituted Area

The new area of data collection was east of area 3 and would cover the entire inlet as seen in Figure 7. The water clarity in this area was significantly better than the original area. In the southernmost portion of the bay, shallow water and marshland made data collection less successful, with extinction depths between 10-15m, and also generated shallow water gaps. This substitution, as well as the extension in this area, added an additional 100km of linear coastline to the Area 3 survey area.

The second substitution involved changing the area 2 survey area from Chequamegon Bay north of Ashland to an area of coastline east from the Wisconsin/Michigan boarder. Water clarity in the Chequamegon Bay was poor throughout the survey with depth penetration less than 10m, with the majority of data collected in the area achieving depths of less than 5 meters. These poor water conditions were attributed to river runoff and the protected nature of the bay not allowing the suspended sediment to easily exit. The substituted area can be seen in Figure 8.

Figure 8 – Area 2 Substituted Area

Water conditions in the substituted area were better than the original area, but remained somewhat marginal due to river runoff along this stretch of coastline. Depth penetration ranged from greater than 20m in areas not affected by river runoff, to less than 5 meters in areas at the mouths of flowing rivers.

2 HORIZONTAL GROUND CONTROL

The 2010 Fugro LADS, Inc. bathymetric lidar survey of the Lake Superior shoreline required a geodetics control network to provide high accuracy positioning throughout the project area. The network consisted of a LADS Base Station at Duluth International Airport (LADSBS), another at Sawyer International Airport for operations on the Keweenaw Peninsula (LADSBSY) and seven Continuously Operating Reference Stations (CORS). Coordination of the LADSBS and LADSBSY each required the occupation of three NGS Survey Marks. The image in Figure 9 depicts the locations for each station of the control network in relation to the survey areas. Tables 7 to 10 describe coordinates and ellipsoidal heights for the control network stations and NGS Survey Marks used to coordinate the LADS base stations and for topographic integration control.

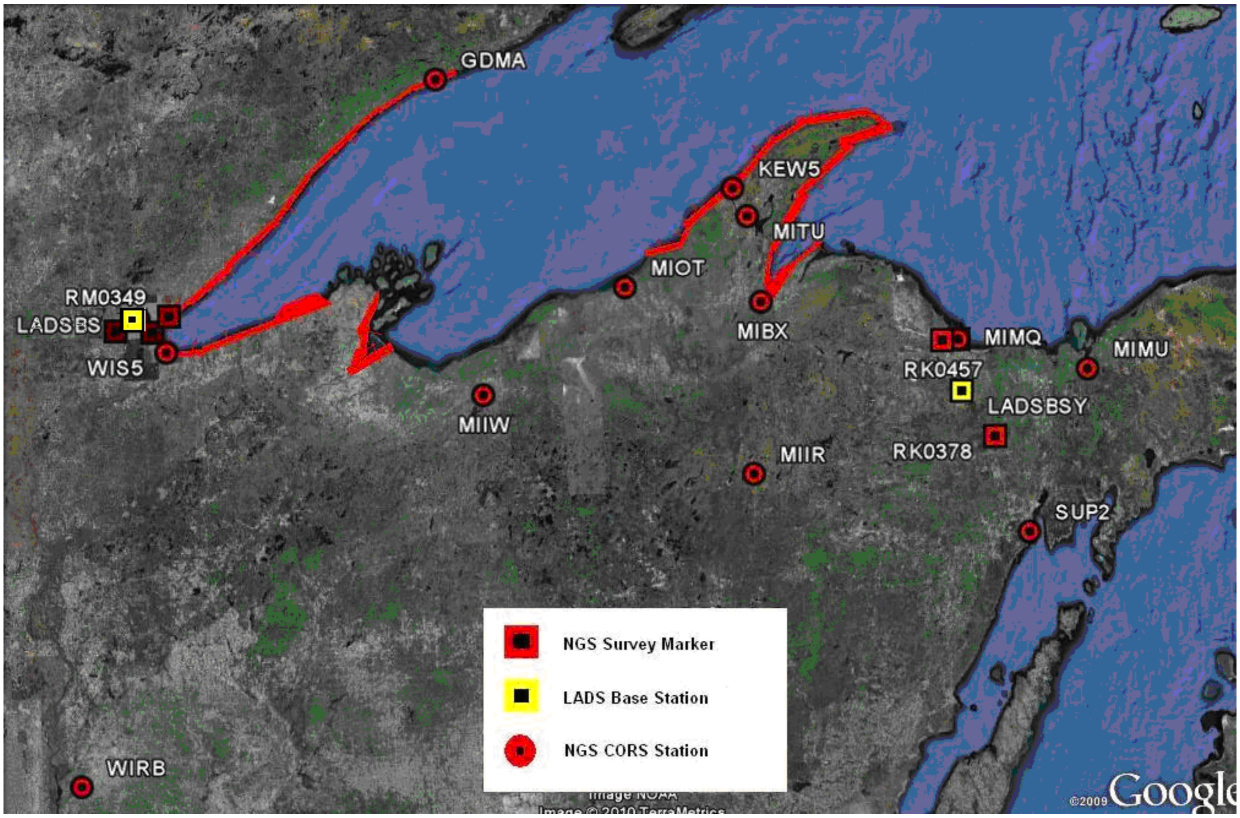

Figure 9 - LADS Geodetics Control Network for Lake Superior 2010

	NAD83		UTM (N)			
Station Name	Latitude (N)	Longitude (W)	Easting (m)	Northing (m)	Elps. Height (m)	Zone
LADSBS	46º 50’ 21.3757”	92º 11’ 34.9973”	561532.078	5187619.213	412.260	15
LADSBSY	46º 20’ 21.8176”	87º 23’ 21.1968”	470046.502	5131831.197	332.449	16
MIIW	46º 28’ 12.8653”	90º 09’ 56.5611”	717594.489	5150200.141	420.084	15
MIOT	46º 51’ 48.5708”	89º 17’ 58.4875”	782029.707	5196645.034	188.727	15
WIRB	44º 57’ 33.4487”	92º 36’ 37.2172”	530733.058	4978502.040	285.981	15
WIS5	46º 42’ 18.1720”	92º 00’ 54.7339”	575280.499	5172858.888	160.256	15
MIIR	46º 04’ 49.3721”	88º 38’ 00.1114”	373708.713	5104275.284	470.993	16
SUP2	45º 44’ 58.1094”	87º 04’ 24.5993”	494283.109	5066215.668	154.800	16
MIMU	46º 22’ 37.4567”	86º 38’ 20.5041”	527760.343	5136007.392	235.695	16
GDMA	47º 44’ 54.7575”	90º 20’ 28.4718”	699286.469	5291776.278	158.242	15
KEW5	47º 13’ 37.4061”	88º 37’ 27.5409”	831227.057	5239689.601	164.675	16
MIBX	46º 45’ 50.7761”	88º 30’ 46.8396”	842603.037	5188733.607	194.713	16

Table 7 - CORS and LADS Stations within the LADS Geodetic Network for Sorties over

Lake Superior, 2010

	NAD83		UTM (N)			
Station Name	Latitude (N)	Longitude (W)	Easting (m)	Northing (m)	Elps. Height (m)	Zone
RN0024	46º 47' 55.5698"	92º 18' 48.7326"	552384.300	5183031.235	379.528	15
AA9913	46º 47' 16.0485"	92º 05' 41.4236"	569087.133	5181980.311	166.727	15
RM0349	46º 51' 00.1290"	91º 59' 30.7339"	576857.559	5188992.685	201.708	15
RK0378	46º 08' 41.3964"	87º 13' 10.8370"	483034.344	5110163.016	279.253	16
AH7272	46º 32' 47.6868"	87º 22' 43.1462"	470970.171	5154848.794	153.107	16
RK0457	46º 32' 52.9815"	87º 28' 30.1093"	463582.168	5155052.181	284.975	16

Table 8 - NGS Survey Marks Occupied to Establish LADS Control Points

		NAD83		UTM (N) Zone 15		
Area	NGS Point	Latitude (N)	Longitude (W)	Easting (m)	Northing (m)	El. Ht. (m)
TIA3	RN1461	46° 48' 25.1526"	092° 03' 51.5154"	571391.958	5184140.638	184.704
TIA9	DG7027	47 °00' 53.0478"	091° 39' 56.1205"	601420.835	5207665.655	159.328
TIA15	RN1694	46° 43' 51.5526"	092° 04' 17.1990"	570947.351	5175688.986	156.548

Table 9 - Base Station / NGS Survey Mark Positions for Topographic Integration Area Surveys

		NAD83		UTM (N) Zone 15		
Area	NGS Point	Latitude (N)	Longitude (W)	Easting (m)	Northing (m)	El. Ht. (m)
TIA3	AA9911	46° 48' 13.2142"	092° 04' 05.5389"	571099.114	5183768.601	174.440
TIA9	RM0346	46° 58' 44.7475"	091° 44' 44.6982"	595391.784	5203604.595	175.011
	AC5009	46° 58' 21.7019"	091° 45' 29.0803"	594465.438	5202878.292	179.488
TIA15	RN1693	46° 42' 42.6945"	092° 02' 39.2725"	573051.538	5173588.453	156.720

Table 10 - NGS Survey Marks used for QC Checks

Additional information on the ground control utilized for this project can be found in Annex 2.

3 VERTICAL CONTROL

The vertical reference for the data collected for this project was to IGLD85. Vertical control for this survey was based upon water level observations from four NOAA NWLON stations and a co-tidal model. As Lake Superior is not significantly affected by tides, the average water level at each site at any one time was generally within 5cm, resulting in little uncertainty in raw depth reduction to survey datum. However, in order to correct for localized atmospheric changes in water level, particularly at Duluth during strong winds from the northeast, a 4 station co-tidal model design within the LADS GS provided adequate vertical control and is displayed below:

NWLON Station	Latitude (N)	Longitude (W)
Ontonagon, MI	46° 52.4'	89° 19.4'
Grand Marais, MN	47° 44.8'	90° 20.4'
Marquette, MI	46° 32.7'	87° 22.7'
Duluth, MN	46° 46.5'	92° 05.5'

Table 11 – Water Level Station Coordinates

At the completion of data collection raw water levels were downloaded from the NOAA COOPS website. The raw data was smoothed with a 5th order polynomial by John Oswald and Associates, after which the smoothed water levels were applied to the raw data prior to quality control and approval of the data.

Station descriptions for each gauge used can be seen in Annex 1. Final water level files have also been submitted along with all GPS files.

4 DATA PROCESSING

4.1 Ground System – Overview

As mentioned in section 1.1.3 the primary functions are:

- Mission planning
- Sortie planning
- Sortie processing
- Quality Control
- Data validation, checking and approval
- Data output

In addition, the GS provides facilities for the generation of survey management plots and reports.

The general layout of the LADS Ground System can be seen in Figure 10 below. The following chapters outline the individual steps taken during a complete project.

Ground System

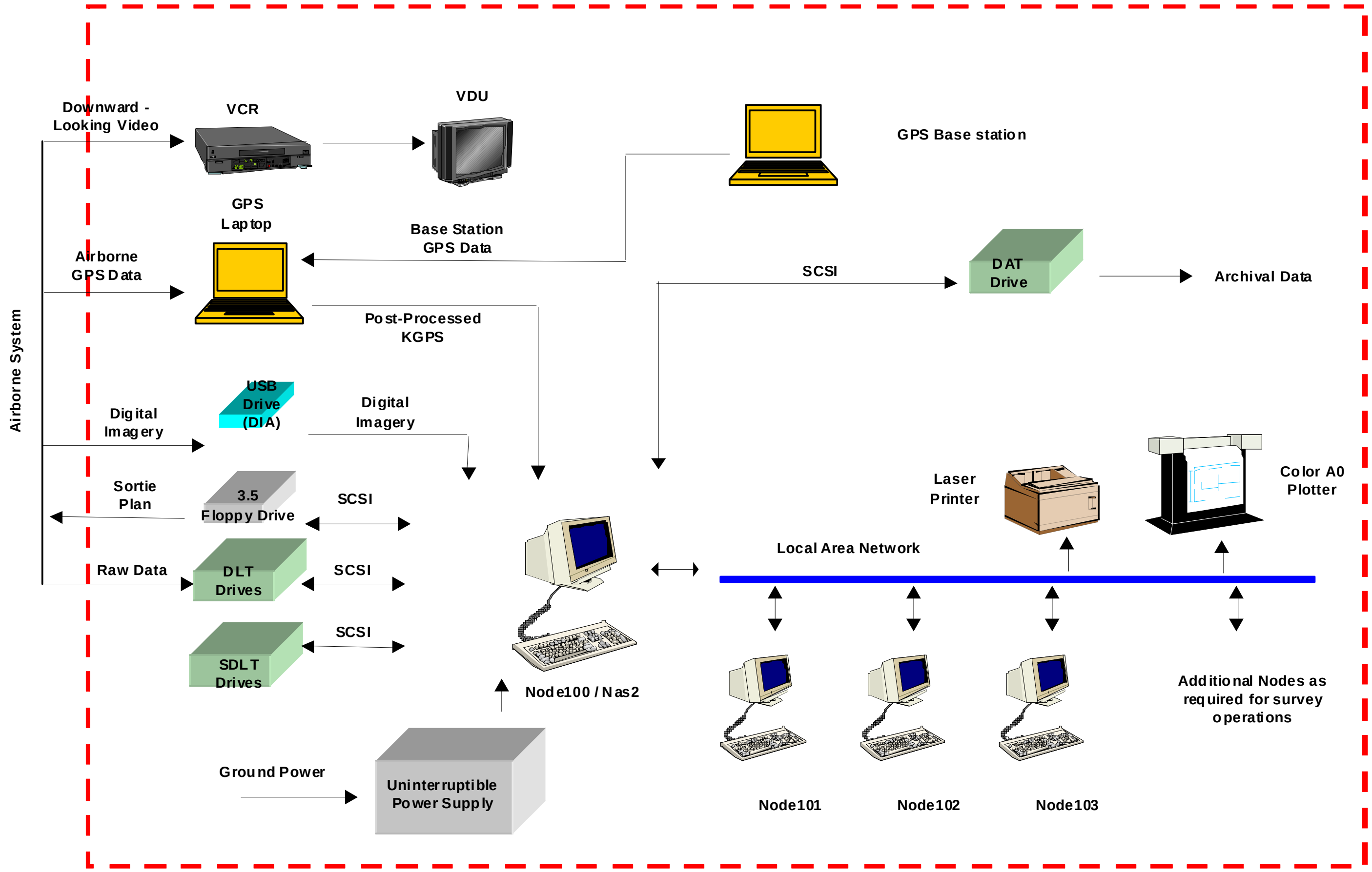

Figure 10 – Block Diagram of the LADS Mk II GS

4.1.1 Mission Planning

At the commencement of a survey, one or more databases are established on the GS. Each database contains spheroid and grid data, tide data and survey objectives.

Sub-areas are defined covering the specific areas to be surveyed. Survey lines are then generated within each sub-area at operator specified line spacing. Other survey lines can be specified by entering start and end coordinates.

4.1.2 Sortie Planning

Prior to each sortie, survey objectives are selected from the appropriate database. The start and end coordinates of the required survey lines are written, together with spheroid and grid data, to a sortie plan on a floppy disk. This plan is read by the AS and used to control sortie operations.

4.1.3 Sortie Processing

Processing parameters are set prior to sortie processing. The post-processed KGPS positions from the local reference station are applied first. Preliminary tides are applied and final verified tides can be reapplied at a later time.

Raw sounding data logged by the AS is automatically processed by the GS to produce depth, position and a series of confidence parameters.

On completion of automatic line processing, operator quality control checks, validation, checking and approval of the sounding data can be conducted.

4.1.4 Data Organization

Data within the GS database is held on a line-by-line basis. Within the survey lines the data is grouped into one-second frames made up of 18 scans of 48 sounding pulses (864 pulses per frame).

4.1.5 Primary and Secondary Soundings

All processed soundings comprise the primary sounding set. Where data set reduction is required, a shoal-biased subset of the primary soundings, called secondary soundings, is created. Secondary soundings form a shoal-biased subset based on operator selected confidence and secondary selection radius criteria. Only secondary soundings are validated, checked, approved and output. For this survey a secondary sounding reduction radial of 1m has been used, which means all soundings have been hydrographically reviewed and all valid soundings have been provided in the final data set. All incorrect secondary soundings were set to Primary during the course of data validation, checking and approval and were excluded from the final dataset.

4.1.6 Automatic Data Processing

Automatic processing is completed in two stages:

1. Sortie Tape Processing (STP).

   STP reads the data on the tape and stores it in the internal GS database for further processing. The data is line-based and consists of raw waveform data, navigation data, platform data, system data, and error and event logs. This process also includes producing a backup of the raw data tape on DAT or DLT.
2. Sortie Run Processing (SRP).

   SRP is the second and major processing phase during which sounding depths and positions are calculated on a line-by-line basis. The process is normally triggered automatically by STP as each line becomes available, but may be invoked later by the operator if reprocessing of lines with different processing parameters is required.

More information on the SRP can be found in Annex 4

4.1.7 Bottom Object Detection (BOD)

A particular feature in the SRP improves the ability of the LADS Mk II GS to detect small objects on the seabed.

The BOD algorithm proceeds in two phases. Each phase can be independently enabled / disabled and tuned via a series of BOD processing parameters set by the operator prior to SRP.

Phase one of the algorithm is designed to detect objects 2-3m in height, while phase two is only invoked if phase one fails. Phase two is more sensitive and intended to find objects less than 2m in height.

4.1.8 Line Reprocessing and Segmentation

It may be necessary to reprocess the same raw sounding data with different processing parameters. The run identification scheme adopted in LADS Mk II provides a mechanism to manage the reprocessing of survey line data multiple times.

After a line is reprocessed, the required segment can then be set to Accepted, and the remaining data can be set to Anomalous or Rejected, and is subsequently excluded from final data output.

5 QUALITY CONTROL

5.1 Data Verification

After data collection and the automated processing is complete the raw data goes through 5 stages of data verification. These steps are listed in table 12 below:

Prevalidation	Checking of automated processing by senior surveyors, with data cleaning of obvious noise, turbidity and datum
Validation	In depth, line-by-line cleaning of Lidar data. Primarily editing soundings on an individual basis, although some broad data filters are used for large areas of false readings. Validation is completed by junior surveyors
Checking	Line-by-line checking of the validation process by senior surveyors, and checking of erroneous soundings highlighted by validators
Quality Control	Area based quality control is conducted by a senior surveyor highlighting features for query by the project manager
Approval	The project manager does a final line-by-line pass ensuring that the final data is correct prior to creating products and deliverables

Table 12 – Data Visualization Process

A complete data verification process and ground system operation can be found in Annex 4.

5.1.1 First Return and Bare Earth Editing

For the Lake Superior project, classification of topographic features was to be assigned as first return or as bare earth soundings. As the LADS waveform does not differentiate between multiple topographic returns, a separate processing step was required to identify data points that were considered bare earth returns.

The processes outlined in section 5.1 were completed, leaving in all topographic data other than features that were not in a fixed position, such as boats, cars and dynamic navigational aids (buoys). These features were removed from the data in the validation phase, whereas first return features were left unedited.

First return soundings include the following:

- Tree returns
- Fixed Navigational Aids
- Jetties
- Buildings
- Bridges
- Other man made features fixed in place

Once completion of first return data processing was achieved, another secondary database was created. This database was a direct copy of the first return database, but was renamed as a bare earth database. This database went through the checking, QC and approval phases again, removing the first return features listed above.

After the completion of bare earth cleaning, LAS exports from both the first return and bare earth databases were generated and delivered to FEDI for classification. A detailed process of classification can be seen in section 7.2.

5.2 Absolute Accuracy Checks

5.2.1 Base Station Confirmation

The two LADS base stations were confirmed to be free of multipath and other site-specific issues by conducting a 24 hour check. The results of this check are:

Solution	Taped Distance (m)	Observed Distance (m)	St. Dev. 1σ Eastings (m)	St. Dev. 1σ Northings (m)	St. Dev. 1σ Positions (m)
KGPS	1.035	1.026	0.012	0.014	0.018

Table 13 – Duluth Base Station Confirmation Results

Solution	Taped Distance (m)	Observed Distance (m)	St. Dev. 1σ Eastings (m)	St. Dev. 1σ Northings (m)	St. Dev. 1σ Positions (m)
KGPS	4.220	4.223	0.013	0.018	0.022

Table 14 – Sawyer Base Station Confirmation Results

Base station confirmation and procedures can be found in Annex 2.

5.2.2 Static

On June 28-29, 2010, static position checks of the LADS Mk II positioning systems were undertaken relative to the aircraft GPS antenna position. Two sessions were performed; the first using Wide Area Differential GPS (WADGPS) and the second using autonomous GPS for real-time positioning. Additionally, during these periods the roving receiver at the aircraft logged data simultaneously with the local GPS base station on the roof of the Monaco Air FBO Hangar. Post-processing of this data provided KGPS (L1 + L2 carrier phase) positions for the aircraft GPS antenna. The real-time GPS positions are relative to the WGS84 reference framework and the post-processed positions are referenced to the NAD83 horizontal datum.

The results of the static calibration are:

Positioning System	Easting NAD83	Northing NAD83			
Absolute Position of GPS Antenna	561559.871	5187545.095			
Session 1	Mean Easting +/- 1σ (m)	Mean Northing +/- 1σ (m)	Δ East C – O (m)	Δ North C – O (m)	Absolute Accuracy 95% Confidence (m)
WADGPS	561560.120 +/- 0.774	5187544.628 +/- 0.883	-0.249	0.467	3.406
KGPS	561559.855 +/- 0.028	5187545.003 +/- 0.009	0.016	0.092	0.165

Table 15 – WADGPS Static Calibration Solution

Positioning System	Easting WGS84	Northing WGS84			
Absolute Position of GPS Antenna	561559.021	5187545.975			
Session 2	Mean Easting +/- 1σ (m)	Mean Northing +/- 1σ (m)	Δ East C – O (m)	Δ North C – O (m)	Absolute Accuracy 95% Confidence (m)
AS autonomous GPS	561560.200 +/- 1.083	5187547.859 +/- 1.277	-1.179	-1.884	6.325
KGPS	561559.133 +/- 0.032	5187545.871 +/- 0.025	-0.112	0.104	0.252

Table 16 – Autonomous GPS Static Calibration Solution

The stated theoretical accuracy of each of the positioning systems has been compared against the absolute accuracy achieved during the static position check in the following table:

Positioning System	Baseline Distance (km)	Theoretical GPS Accuracy 95% Confidence (m)	Absolute Accuracy 95% Confidence (m)	Notes
Autonomous GPS	-	13.0	6.325	
KGPS	0.1	0.3	0.165	1, 2

Table 17 – Comparison Results

Notes

- This solution may be affected slightly by the aircraft not being totally static during the data logging due to wind and personnel movements onboard the aircraft.
- The KGPS solution was the most accurate and within the theoretical accuracy.

Static calibration results and procedures can be found in Annex 3.

5.2.3 Navigation Calibration

Navigation calibration (Navcal) position checks were conducted over three lighthouses within the survey area. Positions for each structure were obtained from the U.S. Coast Guard Light List, Volume II, Great Lakes. Table 18 below shows the results. Large values for navigation check point 1 can be attributed to an incorrectly positioned light house on Manitou Island. This can be assumed as the results over the other two points have good results.

		∆ East (m)		∆ North (m)	
Navigation Check Point	No. of Passes Analyzed	Mean	Standard Deviation	Mean	Standard Deviation
1	4	21.55	4.62	17.35	6.77
3	1	3.30	0.00	1.10	0.00
4	8	1.89	5.63	-1.53	7.01

Table 18 – Navcal Results

More information on the navcal results can be found in Annex 3.

5.2.4 Topographic Integration

A number of discrete areas of ground truth were identified and flown within 1km of the shoreline for integration between bathymetric and topographic lidar. The topographic integration areas were sports fields and parking lots. They were selected for their size, elevation, flatness, and improbability of change over time. Three of the topographic integration areas were surveyed using RTK GPS techniques in order to determine the accuracy of the topographic data acquired by FLI. A comparison between the LADS Mk II data and the RTK data was calculated and the results highlighted in Table 19.

Area ID	Mean Height (above mean lake surface)	Run ID	Number of Comparisons	Mean Vertical Difference (m)	Standard Deviation (m)
TIA 3	32 m	1019.0.1	250	-0.20	0.04
TIA 9	10 m	1003.0.1	509	-0.01	0.15
TIA 15	1 m	1005.0.1	777	-0.13	0.07
TIA 15	1 m	4800.0.1	805	-0.16	0.04

Table 19 – Topographic Integration Results

More information on the topographic integration area check can be found in Annexes 2 and 5.

5.3 Relative Accuracy Checks

5.3.1 Crossties

Throughout the project area, crosstie lines were planned across every sub area, or less than every 25 miles, which ever was a shorter distance. One section of coastline does not meet this requirement, a section of coastline approximately 40 miles long along the western Michigan coastline. This area was one of the last areas to be surveyed and was also an area with vastly changing water clarity. The last of the main flight lines were collected over this area and time did not permit flying a crosstie line over this area. The additional number of crosstie lines over the other sections of the project area ensures that there are ample crosstie comparisons for the entire survey. The results are listed in the table below.

Total Number of intersections	Number of Comparisons	Mean Depth Difference (m)	Mean Standard Deviation
268	563076	0.02	0.14

Table 20 – Crosstie Results

Complete crosstie comparison results can be found in Annex 5

5.3.2 Benchmarks

Following the first sortie in each database suitable benchmark areas were found and benchmark lines were created. At least one benchmark line was flown every second sortie depending on weather and water clarity conditions. The Benchmark results can be seen in table 21.

Total number of benchmarks flown	Total Number Comparisons	Mean MDD (m)	Mean SD (m)	Maximum MDD (m)
14	29305	0.008	0.178	0.12

Table 21 – Benchmark Results

Complete benchmark comparisons and results can be found in Annex 5

5.3.3 Dynamic Results

During each sortie, GPS data was logged both on the aircraft and at the base station, which enabled a KGPS position solution to be determined. These position fixes were then compared to the coordinates as determined by the real-time positioning system. For each survey line the mean difference and standard deviation of position fix differences have been calculated. The following table shows the mean and standard deviation of the difference in position between the real-time positioning system and the post-processed KGPS for each sortie during which data was collected in support of the survey.

The results of the dynamic calibration are:

Mean Difference AS-KGPS (m)	Overall Standard Deviation (m)
1.475	0.173

Table 22 – Dynamic Calibration Results

For more information on dynamic calibration including results per sortie see Annex 3.

6 ASSESSMENT OF ACCURACY

6.1 Vertical Accuracy

An assessment of the final sounding accuracy can be determined by combining the errors due to the LADS Mk II system and the tidal model used. These are combined using a Gaussian model as follows:

σ^2 survey = σ^2 LADS Mk II + σ^2 Tide Model

95% confidence limit = 1.96σ

[For a single dimensional distribution]

Survey Accuracy = $\sqrt{(0.25^2 + 0.15^2)}$ = 0.29m (95% confidence)

From the assessment above, it is considered depth accuracy meets IHO Order-1 standard throughout the survey area. The agreement observed between adjacent survey lines in overlap areas and the crossline comparison results are also consistent with IHO Order-1 depth accuracy.

For more information on determining the LADS Mk II and Tidal errors see Annex 3.

6.1.1 NAD83 Vertical Accuracy

Generation of the LAS format point cloud referenced to the GRS80 ellipsoid required additional transformation from the IGLD85 referenced surface. This additional process adds uncertainty to the vertical component of the soundings. The transformation process is outlined in section 7.3 and more information on the assessment of accuracy is found in Annex 3. This uncertainty is combined with the above results to produce:

σ^2 survey = σ^2 LADS Mk II + σ^2 Tide Model + σ^2 Transformation

95% confidence limit = 1.96σ

[For a single dimensional distribution]

Survey Accuracy = $\sqrt{(0.25^2 + 0.15^2 + 0.025^2)}$ = 0.293m (95% confidence)

The additional uncertainty does not change the above assessment that the depth accuracy meets IHO Order-1 as well as the project accuracy requirement.

6.2 Horizontal Accuracy

6.2.1 LADS Mk II Positioning Accuracy

The total expected error of the LADS Mk II positioning is a combination of the following errors:

- GPS errors (Egps), as stated in Annex 3, have a theoretical maximum of ± 0.65m (95% confidence - KGPS).
- Errors in assigning frame center reference positions from GPS fixes (Eframe ref) have been assessed as ± 0.66m (95%).
- Platform and laser positioning errors (Eplat, this includes such errors as gimbal angles, optical alignment, AHRS angles, AHRS mount, Optical Coupler mount, Scanner mount, Laser output, Laser mount, mirrors, timing and aircraft height). The resultant error in position has been assessed as ± 1.30m (95%).

- **Position errors of detecting objects due to the distance between laser spots (Espot). With a 5m laser spot spacing, it is considered the maximum position error is half of the sample interval distance, or ± 2.5m.**
- **Sea surface errors (Esurface) due to swell. These are variable and dependant on the angle of incidence of the laser beam at the air / sea boundary, the depth of water and sea state. They have been assessed and are tabled below:**

Depth (m)	Sea State 1	Sea State 2	Sea State 3	Sea State 4
5	0	0.03	0.31	0.55
10	0.01	0.06	0.62	1.10
15	0.01	0.09	0.93	1.65
20	0.02	0.12	1.24	2.20

Table 23 – Uncertainty per sea state and depth

Seas were typically calm during survey flights and swell was generally negligible. A maximum sea state of 2 was observed during survey operations, and the general maximum depth achieved by lidar was 20m.

- **Total Expected Error** $= ((Egps)^2 + (Eframe\ Ref)^2 + (Eplat)^2 + (Espot)^2 + (Esurface)^2)^{½}$

The maximum error expected, at 350km from the local GPS base station at Duluth, in a depth of 20m, with sea state 2 is:

- **Total Expected Error** $= ((0.65)^2 + (0.66)^2 + (1.30)^2 + (2.50)^2 + (0.12)^2)^{½}$
  = 2.97m at the 95% confidence level

Analyzing the positional data obtained from both the static and dynamic position checks, it has been concluded that during the survey, IHO Order-1 precision for position was achieved, as well as meeting the project accuracy specification.

6.2.2 GPS Positional Accuracy – Summary

6.2.2.1 Duluth Airport

- **Absolute accuracy of GrafNav post-processed KGPS (0.1km baseline) = 0.165m**

6.2.2.2 Dynamic Position Check

- **Mean value of range distances over all lines of survey between autonomous GPS and post-processed KGPS = 1.475m**
- **Maximum value of range distance, over all lines of survey between autonomous GPS and post-processed KGPS = 12.441m**

6.2.3 Horizontal Accuracy of Final Soundings

- **Theoretical Accuracy**
  (Depth = 20m, Sea State 2, Baseline 350km) = 2.97m

- **IHO Order-1 Horizontal Accuracy**
  (95% confidence) = 5m + 5% of the depth

- **Survey Horizontal Accuracy**
  (95% confidence) = better than 3m

More information on the LADS Mk II horizontal accuracy can be found in Annex 3. For scatter plots and additional information see Annex 5.

6.3 Data Coverage

6.3.1 Bathymetric Coverage

Bathymetric coverage varied throughout the survey area, depending on the water clarity and environmental conditions at the time of the collection impacted the overall result of the coverage. Of the 91 tiles encompassing the entire 3 survey areas 69 tiles have extinctions depths greater than 20 meters with minimal gaps, 14 tiles have extinction depths of 10-20m with some small gaps in the data and 8 tiles have extinctions depths of 5-10m with gaps due to water clarity conditions in close proximity to river runoff areas. The individual tile quality can be seen in figure 11.

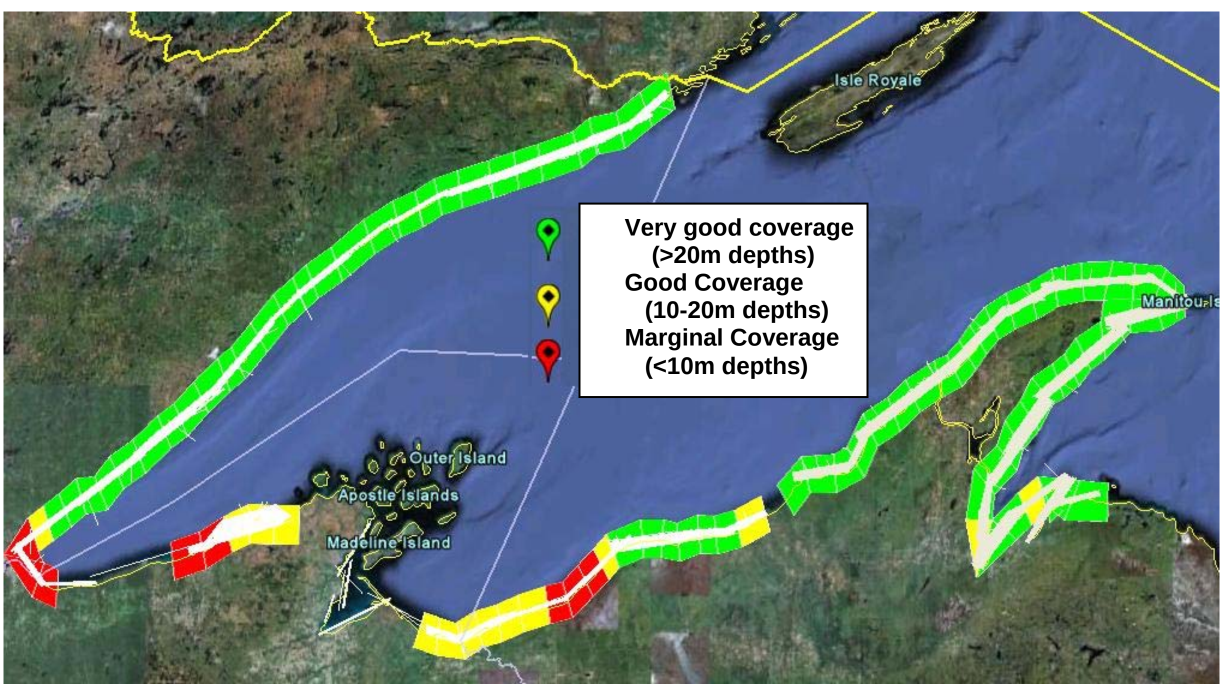

Figure 11 – Tile Quality Indicators across the Entire Survey Area

Although data quality is marginal in area, it was not considered unexpected. Historical data, river runoff and weather studies highlighted these areas as difficult areas for Lidar bathymetry. Areas where data extinction exceeded 25m were unexpected and were considered hugely successful.

Specific gaps in the data can be attributed to:

- Poor water clarity due to river runoff
- Shallow water exclusion in areas on gentle sloping lake bottoms or areas of marsh
- Extremely glassy lake surface conditions in protected areas

Coverage of individual tiles including data quality and gaps is listed in Annex 6.

6.3.2 Topographic Coverage

Topographic coverage was required 30m beyond the coastline for the survey area. Although all coastlines were surveyed to greater than 30m, some areas have topographic coverage less than 30m. This occurred in protected bays where long periods of over land data were collected. The LADS Mk II system uses the lake surface as the vertical reference, therefore after long periods of over land the vertical datum may shift. In these situations the data is set to rejected and reflown.

Topographic coverage is reported on a tile by tile basis in Annex 6.

6.4 Relative Reflectivity

The LADS Relative Reflectivity product represents a measure of the amount of reflected energy from the seabed for each individual laser pulse at the wavelength of the laser, 532nm (green / blue).

Prior to determining the reflectivity for each pulse, each sounding is assessed for suitability. Drying soundings and soundings in very shallow water (<2m depth) are not processed for reflectivity. Also, within the processing workflow, reflectivity processing is undertaken after the raw data has been processed for depth. Soundings for which valid depths were not approved are also removed from the reflectivity processing. During the reflectivity data review depths beyond 20m deep are also rejected, due to the strong correlation between reflectivity and depth in deep water. Following this vetting process suitable soundings are processed to produce reflectivity data.

The entire return waveform needs to be compensated for the electronic gain of the receiver system. The gain control algorithms of the LADS system are complex and not described here. However, functionally this step is straight forward with each sounding normalized for the electronic gain that was applied to the photo multiplier tube to which the received laser energy is optically routed.

The gain normalized return waveform is then analyzed to determine the level of returned energy from the seabed. This is just a simple integration of the segment of the waveform reflected from the seabed. The integration of the waveform from the seabed will produce a numerical value. In order to ensure this value accurately and meaningfully maps variation of seabed reflectivity, it must be normalized for several parameters.

Energy is lost from the pulses transmitted from the aircraft. These losses are attributed to several sources, and to produce a robust reflectivity value, they must be compensated for. These energy loss sources include losses through the air, losses at the air / water interface and losses through the water column, as well as any system specific losses such as optical filtering, receiver field of view or polarization. It is assumed no energy is lost through the air.

The actual path length of the pulse through the air and water is a function of the aircraft height, water depth and angle at which each pulse is transmitted from the aircraft. The loss through the water column is a function of turbidity and water depth. Waveforms are analyzed to determine a beam attenuation coefficient that is then used to calculate loss as a function of water depth. The loss at the air / water interface, whilst not varying significantly with incidence angle given the LADS system geometry, could be expected to vary significantly with increased sea state. Additional losses for the LADS system are due to optical components that are used in some circumstances. The loss of energy attributed to these is also calculated.

The reflectivity algorithm determines the relative reflectivity of the sea bottom using a simple energy summation for each sounding. The transmitted energy is recorded during the survey and the received energy can be found by integrating the bottom pulse in the green waveform. The energy losses along the path of the beam are estimated using models of the physical phenomena, such as light scattering through the water column and diffuse reflection from the sea bottom. Finally, the amount of energy absorbed by the sea bottom is calculated and the reflectivity can be determined.

energy absorbed = energy transmitted – energy received – path losses

Accounting for losses along the path of the beam is complicated, as the amount of scattering and absorption depends on both the depth and turbidity of the water. The reflectivity algorithm allows for either automatic estimation of turbidity from the backscatter through the water column, or the manual input of a turbidity value.

The algorithm is limited to finding the relative reflectivity of the sea bottom, and does not attempt to classify areas into material types such as rock or sand. This is because many different materials will have the same reflectivity, even if they are a different color (because only green light is used). The reflectance data is a relative measure of reflectance, not an absolute measure. For identifying areas of common material types, additional processing and bottom sampling is necessary.

6.4.1 Reflectivity Artifacts

During the calculation and review of the Lake Superior relative reflectivity dataset a number of artifacts were observed. Each of these artifacts could not be resolved and in some instances, were rejected from the final reflectivity dataset. The artifacts observed include:

1. **Near-shore transition. A well defined step in the reflectivity was often observed in close proximity to the shore line, particularly following a long overland passage. These near-shore artifacts were removed from the final reflectance data and imagery.**

2. **Significant change in water clarity. A water clarity estimation parameter is utilized during relative reflectance calculation to model water column losses across lines flown on different days, under different water clarity conditions. However, when there is a large change in water clarity between adjacent lines flown on different days, the losses cannot be modeled adequately and the poorer quality data is rejected. This occurred quite often in Lake Superior within close proximity to rivers and creeks following significant rainfall and subsequent discharge.**

3. **Reflectivity Stepping. A clearly defined linear stepping was observed in the data. This occurred in all depths of water in random locations. The cause of this stepping is currently unknown, but has occurred in subsequent reflectance datasets produced for other customers. This artifact is under current investigation by the Fugro LADS Technical department. Where reflectivity stepping was observed in the Lake Superior dataset it has been rejected.**

4. **Glassy surface conditions and rapid gain change. An artifact, not observed in reflectivity prior to this project, was noted and attributed to the Airborne System hardware. This artifact was apparent only under glassy lake surface conditions. Under such conditions the automated gain control enforced a rapid change in the deep water gain, which could not be adequately modeled for under the current reflectivity algorithm. This issue was investigated by staff in the Fugro LADS Technical department, but significant research and testing returned no improvement in the data. As the issue was hardware related and the gains were not recorded to the level of detail required, a software fix was not possible. This issue has been addressed for future surveys with the implementation of increased automated gain control logging. Unfortunately, this does not resolve the artifacts observed in the Lake Superior project. As this artifact was not systematic and was attributed to localized lake surface conditions, the reflectivity data affected by this artifact were accepted in the final dataset.**

For specific comments on reflectivity gaps per tile see Annex 6

7 PRODUCED DOCUMENTS AND DATA

Below is a list of documents and data that are considered the final deliverables.

- Report of Survey, including the following as annexes:
  - Ground Control Plan
  - Ground Control Report
  - Data Verification Report
  - Absolute Accuracy Checks
  - Relative Accuracy Checks
  - Tile Description Report
  - Directory Structure
  - Verification Certificate
- GPS files, including:
  - Raw airborne and ground GPS data
  - GPS processing projects
  - Processed GPS files
- Verified tides files
- Data coverage images
- Data coverage vector limits
- LAS format point clouds
- Lidar waveform files in CARIS format
- Bare earth 5m DEM
- LADS Relative Reflectance Imagery
- As flown flight lines
- Flight line geodatabase in ArcGIS format
- Digital georeferenced aerial imagery mosaics
- Metadata

For information and naming of final deliverable documents and data see Annex 7.

7.1 Data Coverage Images

First return data was imported into CARIS HIPS/SIPS to generate a coverage raster in geo-tiff format. Each file has the naming convention 2010_GLRI_[ST]_[Tile Number]_Coverage. The coverage image is referenced to the NAD83 ellipsoid and projected using UTM.

7.2 Data Coverage Limits

A shape file delineating the extents of the coverage was generated for each tile. Each file has the naming convention 2010_GLRI_[ST]_[Tile Number]_Covlim. The limit line was created from a TIN surface using a longest face edge of 10m. The coverage limit files are referenced to the NAD83 ellipsoid and projected using UTM.

7.3 LAS Format Point Clouds

LADS raw data was collected using mean lake surface as survey datum. Water level stations around the survey area were used to reduce the soundings to IGLD85. Data

cleaning generated a first return data set and a second bare earth data set, both referenced horizontally to NAD83/UTM and vertically to IGLD85.

The two data sets were delivered to FEDI where the two datasets were merged and classified. Where topographic returns existed in both datasets the return was assigned a bare earth classification, where a return existed only in the first return dataset and not in the bare earth dataset the return was assigned a first return classification. Two final classified LAS files have been delivered. One LAS file is vertically referenced using IGLD85 while the second file is vertically referenced to the NAD83 Datum. Both files are horizontally referenced and projected using NAD83/UTM. Each file has the naming convention 2010_GLRI_[ST]_[Tile Number]_FR_IGLD85 or 2010_GLRI_[ST]_[Tile Number]_FR_NAD83.

7.3.1 Vertical Transformation to NAD83 Ellipsoid

The vertical transformation of the LAS format point clouds was completed by FEDI with the use of ProjMap software.

ProjMap software could transform LAS datasets without losing header information, but did not recognize IGLD85 as a datum for transformation, therefore a work around was developed where the IGLD85 surface would be shifted by a constant 0.03m to reference the dataset to NAVD88, this shift was determined to be accurate to +/-1.5cm by transforming a sample of points within NOAA's vDatum software from IGLD85 to NAVD88, a mean and standard deviation was calculated over this transformed surface determining the 0.03m difference. The NAVD88 referenced data set was then transformed to NAD83 within ProjMap.

These transformation steps have added uncertainty to the vertical position of the data and have been outlined in section 6.1 and in Annex 3.

7.4 Lidar Waveform Files in CARIS format

Waveform data was exported from the GS and delivered in the CARIS HDCS format. These files are referenced to NAD83 geographically. The data originally was referenced to the survey datum which approximates a mean lake surface height value of 0m. However, in order to reference the data vertically to IGLD85 a tide correction of 183.2m was applied. As a result of a CARIS limitation of only being able to display depths/elevations in a positive down manner, the sign of all depth/elevation values is negative.

7.5 Bare Earth DEM

The bare earth data set was generated as a 32-bit geo-tiff with a 5 meter resolution. The DEM is geographically referenced to NAD83, projected using UTM, and vertically referenced to IGLD85. Each file has the naming convention 2010_GLRI_[ST]_[Tile Number]_5mgrid. The bare earth DEM's were created with the use of CARIS and Fugro Workbench software.

7.6 Reflectance Imagery

LADS Relative Reflectance imagery is an 8-bit geo-tiff that was generated using Global Mapper and ArcGIS software. Pixel value 255 was assigned for defining background and can be set to transparent if required by the end user. Each file has the naming convention 2010_GLRI_[ST]_[Tile Number]_RR.

7.7 As Flown Flight Lines

As flown flight lines were delivered in shape file format after completion of data acquisition. The shape file did not contain attribute information for each line.

7.8 Flight Line Geodatabase in ArcGIS format

The flight line geodatabase contains all flight lines for each of the three areas of the Lake Superior survey in ArcGIS format. Each line has been attributed with the LAS_Run_ID, GS_Run_ID, Start_Date, Start_Time, End_Time. The LAS_Run_ID attribute will provide a link to the LAS Source ID field. The geodatabase is referenced to NAD83.

7.9 Digital Imagery Mosaics

During the course of data collection georeferenced imagery is collected in unison with bathymetric data. Individual images are used in the data verification steps. A final mosaic image is generated for quality control of the topographic data. These mosaic images were delivered as an additional product. Some gaps exist in the coverage of the imagery due to a hard drive failure during one flight. In this instance, spaghetti runs were flown as close to the coastline as possible for use in the data verification stage of processing. Georeferenced digital image mosaics are referenced to NAD83 and projected using UTM. Each file has the naming convention 2010_GLRI_[ST]_[Tile Number]_GI and is delivered in ECW format.

7.10 Metadata

For each file type a FGDC compliant metadata file has been generated with the use of TKME software. The metadata files are recorded in xml format.

7.11 Hard Copy Scans

Although listed as a deliverable, discussion with NOAA CSC during the quality control meeting at the FLI office in November highlighted that digital scans of individual flight sheets, field data collection sheets and other daily produced reports were not required. These documents can be made available on request.

All data has been delivered on two separate USB drives. The file names and locations are located in Annex 7

8 ANNEXES

8.1 Annex 1: Ground Control Plan

File name: LADS_Lake_Superior_Ground_Control_Plan.pdf

8.2 Annex 2: Ground Control Report

File name: 2010_GLRI_Ground_Control_Report.pdf

8.3 Annex 3: Vertical and Horizontal Report

File Name: 2010_GLRI_Vertical_&_Horizontal_Report.pdf

8.4 Annex 4: Data Verification Report

File Name: 2010_GLRI_Data_Verification_Report.pdf

8.5 Annex 5: Absolute and Relative Accuracy Checks

File name: 2010_GLRI_Absolute_&_Relative_Accuracy_Report.pdf

8.6 Annex 6: Tile Descriptions

File Names: 2010_GLRI_MI_Tile_Report.pdf
2010_GLRI_MN_Tile_Report.pdf
2010_GLRI_WI_Tile_Report.pdf

8.7 Annex 7: Directory Structure and File Naming Convention

File Name: 2010_GLRI_USB_Directory_Structure.pdf

8.8 Annex 8: Verification Certificate

File Name: LADS_MKII_Performance_Vertification_Cert.pdf