United States Department of Agriculture

NRCS

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SUBJECT: SOI – Geophysical Assistance

March 4, 2011

TO: Vicky Drew
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File Code: 330-7

Purpose:
The purpose of this study is to develop field methodologies and data analysis procedures for the rapid identification, classification, and delineation of subaqueous soils and landscapes from copious ground-penetrating radar (GPR) data sets collected over ice-covered water bodies. Radar data and terrain analysis procedures will be used to identify differences in substrates and distinguish different subaqueous soil-landscape units based on bathymetry, slope, landscape shape, sediment type, and geographical location.

Participants:
Joe Bertrand, Missisquoi NWR Maintenance Mechanic, Missisquoi National Wildlife Refuge, Swanton, VT
Roger Dekett, MLRA Soil Scientist, USDA-NRCS, St. Johnsbury, VT
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
Thomas Villars, Resource Soil Scientist, USDA-NRCS, White River Jct, VT

Activities:
During the period of February 22 to 24, personnel from the NSSC, the Vermont NRCS Soil Resource Staff, and U.S. Fish and Wildlife Service's Missisquoi National Wildlife Refuge (NWR) used a mobile GPR platform to complete more than 52 km (32 miles) of continuous, geo-referenced GPR data recordings across ice-covered portions of Missisquoi Bay in northwestern Vermont.

Summary:

1. Survey work was halted by equipment problems on the third day before the completion of the planned survey work. The SIR-3000's USB port and mother board malfunctioned and the system became inoperative. The unit has been returned to manufacturer for repairs.

2. More than 32 miles of geo-referenced GPR data was collected across the southeast portion of Missisquoi Bay. This effort resulted in 416,692 georeferenced water-depth measurements that were semi-automatically picked from the radar records using processing software. Based on these picks, in the traversed areas, at the time of this

survey, the average water depth was 1.71 m with a range of 0.52 to 3.51 m. One-half of the picks had water depths between 1.02 and 2.42 m.

3. As part of this study, Dr Zamir Libohova (Research Soil Scientist, Soil Survey Research & Laboratory, NSSC) will use GPR data and terrain analysis techniques to quantify terrain parameters (e.g., slope and landform units). This methodology will be used to identify subaqueous soil-landscape units, which can be used to partition submersed areas into more homogenous map units.

4. All interpreted radar data has been forwarded in Excel worksheet formats to Thom Villars and Dr Zamir Libohova for records and use.

It is the pleasure of Jim Doolittle and the National Soil Survey Center to be of assistance to your staff in this study.

JONATHAN W. HEMPEL
Director
National Soil Survey Center

cc:
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Technical Report on Subaqueous Soil Pilot Mapping Project in Missisquoi Bay, Vermont, on 22 and 24 February 2011.

Jim Doolittle

Background:

> "The concept that sediments in shallow water environments undergo soil forming processes, are capable of supporting rooted plants, and meet the definition of soil according to the criteria defined in Soil Taxonomy has been moving soil scientists into a new frontier of soil survey – mapping subaqueous soils." (Jim Turenne, State Soil Scientist, USDA-NRCS, Rhode Island; http://nesoil.com/sas/sasinfo.htm).

Subaqueous soils occur under both fresh and salt waters. These soils have the ability to support rooted plants in natural environments. The maximum water depth limit for subaqueous soils is presently set at 2.5 meters. This depth limit is assumed to represent the "*normal*" maximum depth below which most emergent vegetation will not grow. However, in some areas, emergent vegetation is known to grow at deeper depths.

In order to document, map, and classify subaqueous soils, it is important to have knowledge of water depths, bottom topography, sediment types and thickness, and subaqueous processes. Over open water, acoustical fathometers and acoustic sub-bottom profilers (SBP), and radio-frequency ground-penetrating radar (GPR) have proven to be effective in providing information on water depths, bottom topography, sediment types and thickness (Feurer et al., 2008). However, over open-water these methods, because of drift, often suffer from imprecise positioning with adverse ramifications for the subsequent ground-truth verification of interpretations and the selection of core sites (Moorman and Michael, 1997). In northern latitudes, GPR can also be used on ice-covered water bodies, which provide stable platforms for the more accurate positioning of core sites and the completion of traverses (Hunter et al., 2003).

Ground-penetrating radar has been used extensively for bathymetric surveys of fresh water lakes (Doolittle et al., 2010; Fischer et al., 2007; O'Driscoll et al., 2006; Buynevich and Fitzgerald, 2003; Hunter et al., 2003; Moorman, 2001; Moorman and Michel, 1997; Mellett, 1995; Sellmann et al., 1992; Izbicki and Parker, 1991; Truman et al., 1991; Haeni et al., 1987) and rivers (Sambuelli et al., 2009; Feurer et al., 2008; Spicer et al., 1997; Kovacs, 1991; Annan and Davis, 1977). In these studies, GPR provided continuous, highly detailed, two-dimensional records of subbottom-sediment type, thickness, and topography. These studies illustrate how GPR can provide more comprehensive observations of bottom and subbottom conditions than possible from core data alone. Traditional coring methods are labor intensive, and have very high cost/area ratios (Feurer et al., 2008). As a consequence of these high costs, the number of cores is often limited. Limited measurements and observations often result in the oversimplification of relatively complex subaqueous environments (Stevens et al, 2009). Ground-penetrating radar can provide continuous records of subaqueous substrates, soils, and landforms. Acceptable radar interpretations, however, require a lesser, but still sufficient number of cores for verification.

In reported studies conducted in low-conductivity waters, GPR has been used to identify the water / bottom-sediment interface to depths as great as 22 to 25 m, and provide accurate and detailed bathymetric cross-sections and contour-maps (Moorman and Michel, 1997; Delaney et al. 1992; Sellmann et al., 1992). Moorman and Michel (1997) reported an accuracy of ± 3% for GPR measurements of lake bottoms to depths as great as 19 m. However, in conductive waters, GPR is more depth restrict. The use of GPR in brackish or salt waters is impractical because of their high electrical conductivity and attenuation rates, which severely restricts penetration.

The purpose of this investigation was to obtain data with GPR on water depths, bottom topographies, and sediment types within the southeast portion of Missisquoi Bay, Vermont. This information will be used to develop field methodology and data processing techniques for the rapid assessment and mapping of subaqueous soils in bodies of fresh water.

Equipment:
The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000 (here after referred to as the SIR-3000), manufactured by Geophysical Survey Systems, Inc. (GSSI; Salem, NH).[1] The SIR-3000 consists of a digital control unit (DC-3000) with keypad, SVGA video screen, and connector panel. A 10.8-volt lithium-ion rechargeable battery powers the system. The SIR-3000 weighs about 9 lbs (4.1 kg) and is backpack portable. With an antenna, the SIR-3000 requires two people to operate (Fig. 1, right). Jol (2009) and Daniels (2004) discuss the use and operation of GPR. A 200 MHz antenna was used in this study.

Figure 1. Both mobile and pedestrian surveys were conducted across the ice-covered southeast portions of Missisquoi Bay.

The RADAN for Windows (version 6.6) software program (GSSI) was used to process the radar records.[1] Processing included: header editing, setting the initial pulse to time zero, color table and transformation selection, range gain adjustments, signal stacking, and migration (refer to Jol (2009) and Daniels (2004) for discussions of these techniques).

Recent technical developments allow the integration of GPR and GPS data. The SIR-3000 system provides a setup for the use of a GPS receiver with a serial data recorder (SDR). With this setup, each scan on radar records can be georeferenced (position/time matched). Following data collection, a subprogram within the RADAN is used to proportionally adjust the position of each radar scan according to the time stamp of the two nearest positions recorded with the GPS receiver. A Trimble AgGPS114 L-band DGPS (differential GPS) antenna (Trimble, Sunnyvale, CA) was used to collect position data.[1] Position data were recorded at a time interval of one second along GPR traverse lines. The scanning rate of the GPR was set at 24 scan/sec.

[1] Trade names are used for specific references and do not constitute endorsement.

Using the *Interactive 3D Module* of the RADAN, depths to the water/bottom-sediment interface were semi-automatically and reasonably accurately picked, and outputted to a worksheet (X, Y, Z format; including latitude, longitude, depths to interface or layer, and other useful data).

Field Methods:
Both mobile and pedestrian surveys were conducted across the ice-covered, southeast portions of Missisquoi Bay. A track vehicle (Figure 1, left) was used as a mobile platform to rapidly complete GPR surveys across most of the study area. Limited pedestrian surveys (Figure 2, right) were conducted to fill in gaps in data and to obtain ground-truth core observations needed to confirm radar interpretations. The 200 MHz antenna was either mounted in a sled and towed behind the track vehicle for mobile surveys or was pulled by hand to complete pedestrian surveys. Over a 2.5 day period, more than 52 km (32 miles) of continuous, geo-referenced GPR data were recorded.

Calibration:
Ground-penetrating radar is a time scaled system. The system measures the time that it takes electromagnetic energy to travel from an antenna to an interface (e.g., soil horizon, stratigraphic layer, lake bottom) and back. To convert the travel time into a depth scale, either the velocity of pulse propagation or the depth to the reflector must be known. The relationships among depth (D), two-way pulse travel time (T), and velocity of propagation (v) are described in the following equation (Daniels, 2004):

$$v = 2D/T \qquad [1]$$

The velocity of propagation is dependent upon the relative dielectric permittivity (E_r) of the profiled material(s). The relationship between E_r and v is embedded in the large dielectric contrast between water (~80) and air (~1) and is expressed in the equation (Daniels, 2004):

$$E_r = (C/\, v)^2 \qquad [2]$$

Where C is the velocity of propagation in a vacuum (0.298 m/ns). Typically, velocity is expressed in meters per nanosecond (ns). In earthen materials, the amount and physical state (temperature dependent) of water have the greatest effect on the E_r and v.

Estimating Er and v over variable hydrothermal structures is a challenging task. Ground-truth core data were collected at several *reference* or *calibration points* along GPR traverse lines. Measured ground-truth core data from last year's GPR survey on Missisquoi Bay were also incorporated into the present calibration. Based on data from 10 calibration points, the average v though a column of snow, ice, and shallow water is 0.0476 m/ns, but actual values range from about 0.0355 to 0.0776 m/ns. The average E_r though this column is 48.6, but actual values range from about 15 to 71.3. At some core sites, there was essentially no water column and the probe went from ice directly into subaqueous soil materials. The velocity of propagation increases and the dielectric permittivity decreases as the water column shallows and the relative thickness of the ice column increases (compared with underlying water column). Ice can have an E_r that ranges from 3.5 to 8 (Kovacs and Morey, 1990); water has an E_r of about 80.1 at 20 ^{o} C, but is frequency and temperature (its 88 at 0^o C) dependent (Daniels, 2004). The E_r of ice decreases and the v increases with increasing snow and ice thickness (Kovacs and Morey, 1990). The dielectric permittivity of the snow cover is a function of its density and unfrozen liquid water content (Lundberg et al., 2000). The dielectric permittivity of dry snow ranges from 1 to 2, while values for wet snow have been reported to be as high as 7 (Sand and Bruland, 1998).

At the 10 calibration sites, a high correlation ($r^2 = 0.959$) was determined between the measured two-way travel time (ns) and the measured depth (m) to bottom sediments (Figure 2). A linear predictive equation was developed and used to estimate the depth to bottom sediments on radar records. This predictive equation is:

$$\text{Depth} = 0.0156*(\text{travel time}) + 0.377 \qquad [3]$$

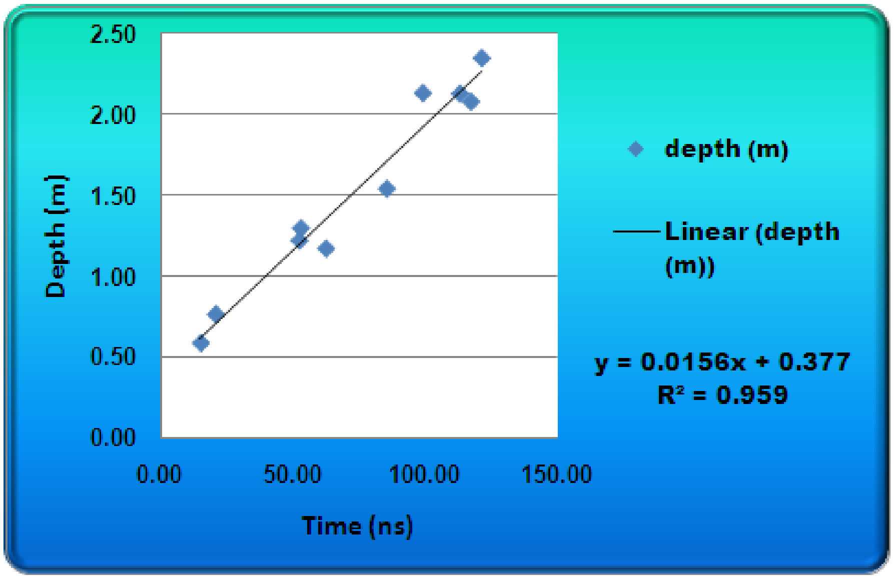

Figure 2. Relationship between measured depths to lake bottom-sediments and the two-way pulse travel time of the GPR.

Table 1. Measured two-way pulse travel time and depths to bottom sediments, and the estimated depths from equation [3].

Time (ns)	Depth (m)	Estimated Depth	Difference
15.06	0.58	0.61	0.03
20.71	0.76	0.70	-0.06
52.24	1.22	1.19	-0.03
52.79	1.30	1.20	-0.09
62.35	1.17	1.35	0.18
85.29	1.54	1.71	0.17
98.92	2.13	1.92	-0.21
112.94	2.13	2.14	0.01
117.06	2.08	2.20	0.12
121.18	2.35	2.27	-0.08

Table 1 examines the relationship between the two-way pulse travel time and the measured depths to the bottom sediments at the 10 calibration points. Using equation [3], the estimated depths to bottom sediments are listed in column 3 of this table. The average difference between measured and estimated depths to bottom sediments (column 4) is 10 cm, with a range or 3 to 21 cm.

Study Sites:
The focus of this study was the southeastern portion of Missisquoi Bay in Franklin County, Vermont (Figure 2). Both Goose and Gander Bays were included in the survey area.

Results:
Figure 2 is a *Goggle Earth* image of the area that was surveyed with GPR. In this image, the locations of the GPR traverse lines are shown. Each traverse line is colored-coded based on the interpreted depth to the water/bottom-sediment interface. Along some radar traverses, the bottom sediments consisted of organic soil materials. The estimated depths that are shown in Figure 2 are based on an average *v* of 0.046 m/ns and an *Er* of 42.5 (not the estimated and *preferred* depths derived from equation [3]).

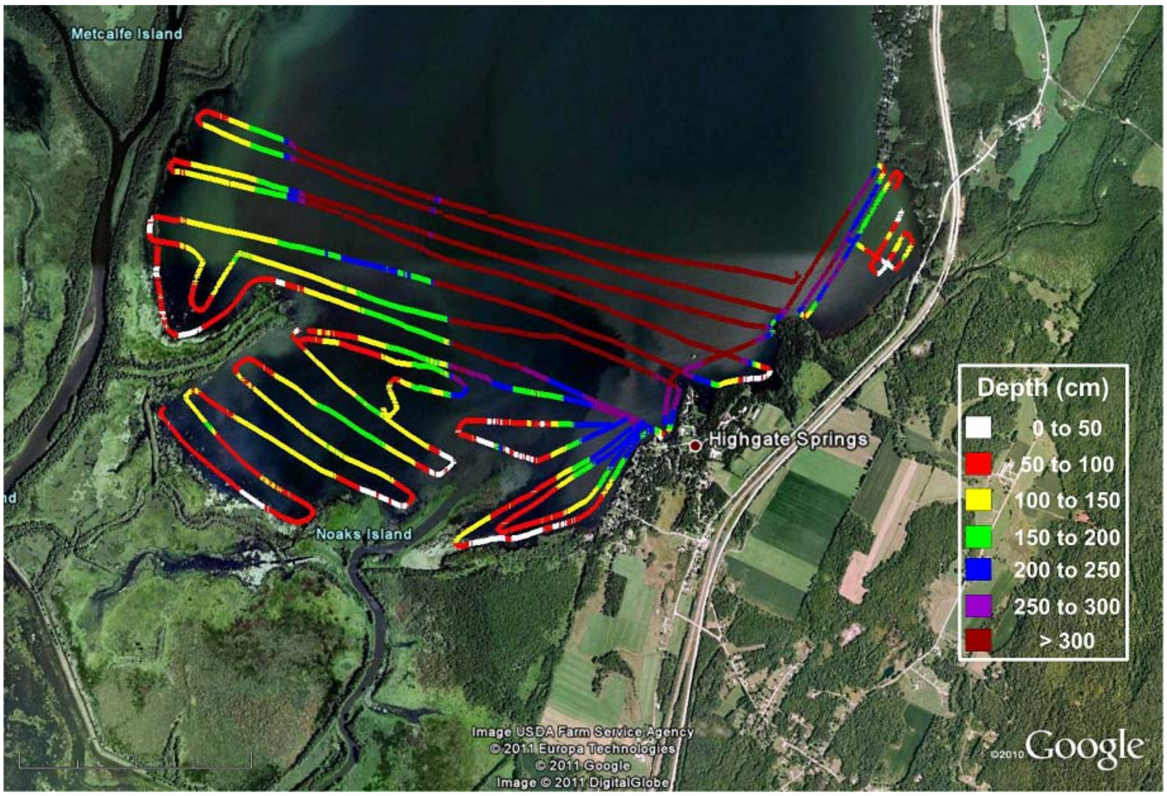

Figure 2. This Google Earth image shows the locations of GPR traverses and the interpreted water depths in the portion of Missisquoi Bay that was surveyed with GPR.

GPR Methodology and Processing Concerns:

1. Estimating the averaged *Er* and *v* over variable hydrothermal structures (snow-ice-water-sediment) is a challenging task. Multi-layer velocity modeling would improve depth estimates, but were not practical with existing technology and resources.

2. Because of the variable hydrothermal structures that exist in snow- and ice-covered water bodies in winter in higher latitudes, water depths must be confirmed thru coring. A sufficient number of cores must be extracted over different ice thicknesses and water depths to accurately depth scale the radar imagery.

3. Fractures in the ice produce hyperbolic reflections on GPR records. Roughness in the ice surface and snow cover over fractures is partially responsible for these patterns. These unwanted reflections interfere with the tracing of the water/bottom-sediment interface. In addition, the velocity of signal propagation is altered beneath these reflectors.

4. In some shallow-water areas (<0.6 m), the water/bottom-sediment interface occurred at or near the same time interval as the ice-bottom multiples, producing interference and ambiguity in bathymetric estimates and the identification of soil materials.

5. Positional accuracy of GPR measurements collected with different platforms (mobile and pedestrian) and with different speeds of advance is a concern. In addition, the GPR antenna was towed behind a track vehicle at a distance of about 6 to 8 feet from the GPS receiver.

6. The elevation of the lake level was 30.02 m (98. 5 feet) at the time of this survey. Ice thickness ranged from 13 to 58 cm (13 to 23 inches).

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