United States Department of Agriculture

NRCS

Natural Resources Conservation Service
National Soil Survey Center
Federal Building, Room 152
100 Centennial Mall North
Lincoln, NE 68508-3866

Phone: (402) 437-5499
FAX: (402) 437-5321

SUBJECT: MGT – Trip Report - Geophysical Assistance January 23, 2012

TO: Vicky M. Drew
State Conservationist
NRCS, Colchester, Vermont

File Code: 330-20-7

Purpose:
An exploratory ground-penetrating radar (GPR) investigation was conducted across specific landforms identified on LiDAR (Light Detection and Ranging) images of the White Mountain National Forest (WMNF), New Hampshire. The purpose of this study is to evaluate the potential of incorporating GPR into the knowledge-based digital soil mapping techniques.

Participants:
Roger DeKett, Soil Scientist, NRCS, St. Johnsbury, VT
James A. Doolittle, Research Soil Scientist, Soil Survey Research & Laboratory, NSSC, NRCS, Lincoln, NE
Robert F. Long, Soil Scientist, NRCS, St. Johnsbury, VT
Jessica M. Philippe, Soil Scientist, NRCS, St. Johnsbury, VT

Activities:
Field work was completed during the period of September 20 - 22, 2011.

Summary:

1. Profuse, georeferenced ground-penetrating data can help soil scientists overcome issues of data insufficiency and incorrectness, validate differences in parent materials and depths to bedrock, and improve the knowledge-based digital soil mapping model of the WMNF. Ground-penetrating radar also provides data on map unit composition and helps correlate common data map units.

2. Within the WMNF, GPR provided ample penetration depth and resolution of many subsurface features, and clearly identified stratigraphic and bedrock interfaces. However, the presence of complex cradle-knoll micro-topographies, large rock fragments, and fallen and standing tree limbs caused poor antenna coupling and jolting that resulted in degraded signal quality and high levels of background noise, which reduced the interpretability of radar imagery.

3. In many of the observed soil profiles examined during the course of this study, the upper 50 cm consists of closely-space organic and mineral horizons of varying thicknesses. These layers were difficult to distinguish and trace laterally on radar records that were collected with a 400 MHz antenna. Using a higher frequency, 900 MHz antenna could improve the identification and interpretations of these closely spaced layers.

4. At the time of this survey, the forest canopy was too impenetrable and limiting for appropriate GPS reception. Poor satellite reception and multipathing resulted in the corruption of the positional data. As a consequence, GPR data could not be georeferenced. It is recommended that

any future GPR work using GPS in New Hampshire and Vermont should be conducted with the leaves off. In addition, areas of coniferous trees should be avoided where possible.

5. On most radar records, a major subsurface interface has been identified that separates two distinct and recurring radar facies. The upper radar facies, with the exception of the surface pulse and several seemingly segmented, near-surface planar reflections (undoubtedly soil horizon interfaces) is relatively free of reflectors. The lower facies consists of numerous, often chaotically arranged point and segmented planar reflections. The planar reflections suggest some water-sorting of the materials. While the identity of the lower facies in unknown at this time, its persistent occurrence on most of radar records is significant and worthy of further investigations.

6. Based on the experiences of this study, GPR field methodologies have been modified for work in similar settings.

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

/s/ Jonathan W. Hempel

JONATHAN W. HEMPEL
Director
National Soil Survey Center

cc:
Stephen H. Gourley, State Soil Scientist, NRCS, Colchester, VT
David Hvizdak, State Soil Scientist/MO Leader, NRCS, Amherst, MA
Robert F. Long, Soil Scientist, NRCS, St. Johnsbury, VT
Kimberly L. McCracken, Assistant State Conservationist, NRCS, Durham, NH
John W. Tuttle, Soil Scientist, Soil Survey Research & Laboratory, NSSC, MS 41, NRCS, Lincoln, NE
James A. Doolittle, Research Soil Scientist, Soil Survey Research & Laboratory, NSSC, MS 41, NRCS, Lincoln, NE
Larry T. West, National Leader, Soil Survey Research & Laboratory, NSSC, MS 41, NRCS, Lincoln, NE
Michael A. Wilson, Research Soil Scientist, Soil Survey Research & Laboratory, NSSC, MS 41, NRCS, Lincoln, NE

Technical Report on Ground-Penetrating Radar Investigations conducted in the White Mountain National Forest, New Hampshire, on September 20 – 21, 2011.

Jim Doolittle

Background:
The White Mountains are a large batholith that forms a distinct physiographic section within the New England province. The White Mountains are composed mostly of granitic rocks, but the higher peaks of the Presidential Range are schist (Van Diver, 1987). The granites weather to form coarse and moderately-coarse textured soils, which, because of their low clay contents, are ideally suited to GPR. In these soils, very deep radar penetration is possible even with higher frequency (> 400 MHz) antennas. Compared with lower frequency antennas, higher frequency antennas provide higher resolution of soil, stratigraphic, and lithologic layers. This study addresses the potential of GPR to identify and estimate the depth to densic materials and bedrock in upland soils encountered in the White Mountain National Forest (WMNF), New Hampshire. Soil catenae explored include the Cabot (loamy, mixed, active, nonacid, frigid, shallow Typic Humaquepts), Colonel (loamy, isotic, frigid, shallow Aquic Haplorthods) and Dixfield (coarse-loamy, isotic, frigid Aquic Haplorthods), which form on basal tills; and the Tunbridge (coarse-loamy, isotic, frigid Typic Haplorthods) and Lyman (loamy, isotic, frigid Lithic Haplorthods), which formed on over shallower to bedrock landforms.

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 4.1 kg (9 lbs) and is backpack portable. With an antenna, the SIR-3000 requires two people to operate. A 400 MHz antenna was used in this study. Jol (2009) and Daniels (2004) discuss the use and operation of GPR.

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, signal stacking, migration, horizontal high pass filtration, and range gain adjustments (refer to Jol (2009) and Daniels (2004) for discussions of these techniques).

Recent technical developments allow the integration of GPR and global positioning system (GPS) data. The SIR-3000 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). During data processing, a subprogram within 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 AgGPS 114 L-band DGPS (differential GPS) antenna (Trimble, Sunnyvale, CA) was used to geo-reference the radar data. [1]

Calibration of GPR:
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, bedrock, stratigraphic layer) and back. To convert the travel time into a depth scale, either the velocity of pulse propagation or the depth to a reflector must be known. The relationships among depth (D), two-way pulse travel time (T), and velocity of propagation (v) are described in equation [1] (after Daniels, 2004):

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

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

The velocity of propagation is mainly affected by the relative dielectric permittivity (E_r) of the profiled material(s) according to equation [2] (after Daniels, 2004):

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

Where C is the velocity of propagation of electromagnetic energy in a vacuum (0.2998 m/ns). The velocity of pulse propagation is most commonly expressed in meters per nanosecond (ns). In soils, the amount and physical state (temperature dependent) of water have the greatest effect on the E_r and *v*.

Based on the measured depth and the two-way pulse travel time to known subsurface reflectors (e.g., dense till, coarser mineral layer, ortstein), the velocity of propagation and the relative dielectric permittivity of the upper part of soil profiles were estimated using equations [1] and [2]. At the time of this study, soils were very moist, but varied spatially and with depth in moisture contents. Depending on landscape position and soil drainage, the estimated E_r for the upper 60 cm of the soil profile varied between 7.4 and 35. The estimated *v* for the upper 60 cm of the soil profile ranged from 0.0502 to 0.1102 m/ns. For the radar records of the soil materials shown in this report, an averaged E_r of 12 and an averaged *v* of 0.0865 m/ns were used based on core observations made along the radar traverse lines. Granite has an E_r that ranges from 5 to 8 and a *v* that ranges from 0.1338 to 0.1071 m/ns (Cassidy, 2009). For the radar record of granite shown in this report, an E_r of 5 and a *v* of 0.1338 m/ns were used.

Resolution:
At the beginning of this study, it was immediately apparent that the GPR could not adequately resolve shallow, closely-spaced soil horizons. Resolution is defined as the smallest separation or discontinuity that can be discerned between two discrete targets, layers, or events. The achievable vertical resolution limit is dependent on the propagated pulse width and the depth to the feature. For two separate soil layers to be distinguishable on a radar record, they must be separated in time by at least ½ the pulse width (Annan, 2001). If two events (e.g., soil horizons, stratigraphic layers) are separated in time by less than this amount they will be indistinguishable and interpreted as one event (Annan, 2009). The vertical resolution can be estimated using the following equation (after Daniels, 2004):

$$R_v = \tau C/2\sqrt{E_r} \qquad [3]$$

Where:

R_v = vertical resolution
τ = pulse width (ns)
C = speed of light in vacuum (0.2998 m/ns)
E_r = relative dielectric permittivity of the medium

The pulse width of the 200, 400 and 900 MHz antennas are about 5, 2.5, and 1.1 ns, respectively. In this investigation, the estimated E_r for the upper 60 cm of the soil varied between 7.4 and 35. Using Equation [3] and this range in Er, the achievable vertical resolution limits vary from about 18 to 28 cm for a 200 MHz, 6 to 14 cm for a 400 MHz, and 3 to 6 cm for a 900 MHz antenna. Interfaces spaced closer together than these values will be superimposed and difficult to identify. In many of the observed soil profiles examined during this study, the upper 60 cm contained several closely-space organic and mineral horizons of varying thicknesses. These layers were difficult to identify and trace laterally on radar records collected with a 400 MHz antenna. Using a higher frequency, 900 MHz antenna could improve the identification and interpretations of these closely spaced layers.

Figure 1. Densely vegetated terrains with highly irregular micro-topographies limited the effectiveness of both GPR and GPS. Image is courtesy of Jessica Philippe.

GPR Survey Procedures:
At each site, multiple traverses were completed with a 400 MHz antenna. The 200 MHz antenna is too wide and cumbersome to negotiate densely forested settings (Figure 1). In moderately-coarse textured till deposits, the smaller 400 MHz antenna provided excellent resolution of subsurface features and ample penetration depths. Each radar traverse was stored as a separate file. At the time of this survey, the forest canopy proved to be too dense and limiting for appropriate GPS reception. Poor satellite reception and multipathing resulted in the corruption of the GPS data. As a consequence, GPR data could not be georeferenced. It is recommended that any future GPR work using GPS should be conducted when the leaves are off. In addition, areas of coniferous trees should be avoided where possible.

The uneven "*cradle-knoll*" micro-topography, fallen tree limbs, and substantial forest undergrowth (see Figure 1) resulted in excessive tilting and discontinuous coupling (contact) of the antenna with the ground surface. Surface roughness affects antenna radiation and waveform characteristics (Radzevicius et al., 2000). The excessive lateral tilting and discontinuous coupling of the antenna with the ground surface, the jarring or the antenna against trees, and the lifting of the antenna over fallen logs produced high levels of background noise that complicated radar records, lowered data quality, fostered ambiguous interpretations, and lowered confidence in the assessments of soil horizons and features.

Study Sites:
Study Site 1 consists of a long traverse through a densely wooded area that was identified as being underlain by basal till at relatively shallow depths. The traverse began near 43.995^{o} N. Latitude, 71.418^{o} W. Longitude; turned at 43.997^{o} N. Latitude, 71.416^{o} W. Longitude; and ended near 43.998^{o} N. Latitude, 71.413^{o} W. Longitude. Study Site 2 is an exposed area of granite that outcrops along a stream channel (Figure 2). The site is located near 44.015^{o} N. Latitude, 71.43^{o} W. Longitude. Study Site 3 is in a

densely wooded area identified as being underlain by basal till at relatively shallow depths. The site is located near 44.014^{o} N. Latitude, 71.43^{o} W. Longitude. This short traverse line was carefully cleared of all obstructing debris and vegetation prior to the radar survey.

Figure 2. At Study Site 2, a radar survey is conducted along an exposed area of granite that forms the base to a mountain stream. Image is courtesy of Jessica Philippe.

Results:

The limitations imposed by soil, vegetation and terrain conditions on both GPR and GPS quickly became evident at Site 1. The dense vegetation entangled both GPR and GPS cables, limited the reception of satellites for GPS, and produced excessive levels of background noise on radar records. At the end of the survey it was obvious that the field methods being employed were not suited to this environment.

Figure 3 is a portion of a radar record from Site 1. On this radar record, all scales are expressed in meters. The 400 MHz antenna provides satisfactory exploration depths and high resolution of subsurface features. However, many of the subsurface layers and features are indecipherable because of excessive background noise. Small scale heterogeneities in the soil (e.g., roots, burrows, rock fragments) extract energy as scattering and absorption losses. Scattering losses are high and considered a significant source of signal attenuation in the forested, till-derived soils of the White Mountains. In Figure 3, it is evident to the experienced eye, that the antenna was not moved at a constant speed along this traverse line and suffered multiple collisions with obstacles in the landscape. Movement was frequently halted by obstacles (e.g., tree limbs, longs, exposed rock fragments). In Figure 3, a tree caused two exceptional jarring episodes in the movement of the antenna. These episodes produced two reverberating, high-amplitude (colored white, grey, pink and green in this display) reflections that are separated by a stable, motionless pattern (highlighted by two inclined arrows) on the radar record. Also highlighted by arrows (horizontal) are two additional jarring events. On closer inspection, other jarring events are evident as minor vertical patterns

on this radar record. The antenna passing over a fallen log produce a noticeable interruption in the continuity of the surface pulse (see arrow near 22 m on the horizontal scale) and reverberated, high-amplitude echoes below. This clutter significantly reduces the clarity of the radar records and decreases confidence in offered interpretations.

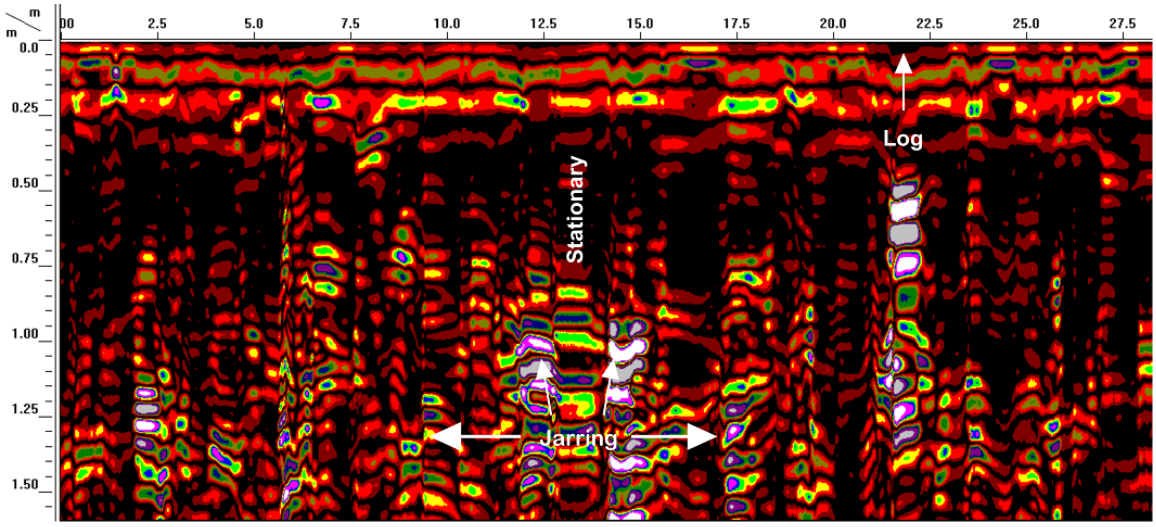

Figure 3. In this representative radar record from Study Site 1, several sources of noise, which impair image quality and interpretability, have been identified.

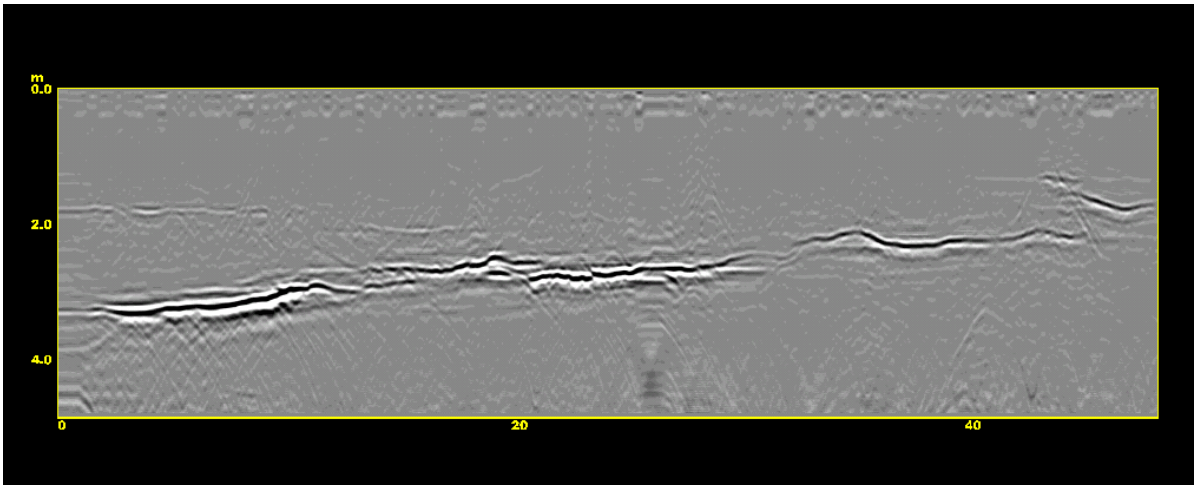

Figure 4. This radar record was collected over the granite surface shown in Figure 2. The granite is transparent to GPR with a depth of exploration of 4.84 meters. A fracture trace is evident within the bedrock.

Site 2, an exposed granite surface, was an area of especial interest as it confirmed the radar facies of granite. Radar facies are "groups of radar reflections whose parameters (configuration, amplitude, continuity, frequency, interval velocity, attenuation, dispersion) differ from adjacent groups" (Baker, 1991). Figure 4 is the radar record from Site 2. With the exception of fracture planes, the granite is

virtually free of subsurface reflections. Two major fracture traces are evident on this radar record between depths of about 1.5 and 3.5 m. The higher-amplitude, linear reflection that spans the entire radar record does vary in signal amplitude and has faulting or fracturing offsets. Variations in signal amplitude are produced by differences (moisture content, weathered materials, air) in the materials filling the fractures. A water-filled fracture will produce a higher amplitude reflection than an air-filled fracture. A second, more horizontal fracture trace is evident in the left-hand portion of the radar record at a depth of about 2 m.

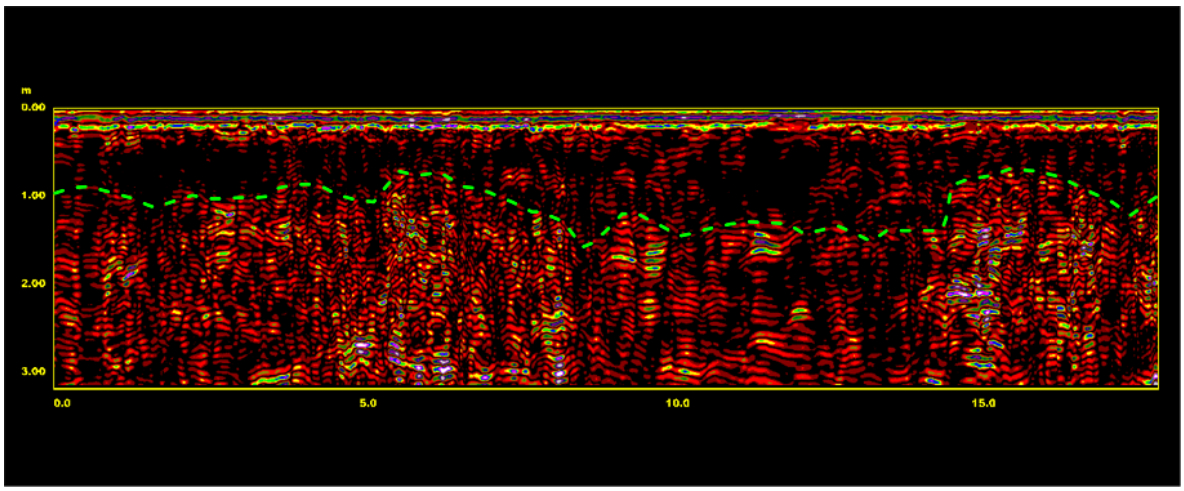

Figure 5. On most of the radar records that were collected in the White Mountains, an unidentified deeper layer of contrasting soil materials was present. The interface that separates this lower layer from the surficial materials has been highlighted with a segmented green-colored line.

Figure 5 is a radar record from Site 3. This traverse was conducted across an area that had been cleared of debris and vegetation, which would have obstructed the steady movement of the antenna. Compared with the uncleared (of debris) traverse (see Figure 3), this radar record has less background noise and clutter, and is more interpretable.

In Figure 5, a segmented, green-colored line has been used to highlight an interface that separates two radar facies. The upper radar facies, with the exception of the surface pulse and several seemingly segmented, near-surface planar reflections (undoubtedly soil horizon interfaces), is relatively free of reflectors. The lower facies consists of numerous, seemingly chaotically arranged point and segmented planar reflectors. The planar reflections suggest some degree of water-sorting of the materials. While the identity of the lower facies in unknown at this time, its persistent occurrence on a majority of radar records is worthy to note. In addition, no bedrock interface was observed on the radar records collected at Sites 1 and 3. For these sites, the depth to bedrock is very deep.

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