Appendix 1

How ground penetrating radar (GPR) works

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Ground penetrating radar (or GPR) uses the transmission and reflection of radio waves (typically 25 to 2 GHz) in imaging the subsurface. Radar waves, introduced in the ground, may reflect back to surface when they intersect objects or surfaces of varying dielectric permittivity. Thus a GPR system requires a source antenna and receiving antenna (built to measure the same frequency). *Note that the plural of electrical devices is antennas; antennae are exclusively for animals such as insects. The transmitting antenna generates a pulse of radiowaves that the receiver detects at a set time interval: the longer the time interval, (potentially) the deeper the waves will have travelled into the ground (or to a nearby surface object) and back again. When the ground has a slow radarwave velocity, so a buried object may appear deeper than in ground with a fast transmissive velocity. As the antennas pass over discrete objects with different dielectric properties to the surrounding medium (boulders, pipes, coffins, trenches), they may generate hyperbolae, or arc-like reflections, or depressions. Radar waves also travel horizontally from the transmitting antenna, which in open ground simply dissipate with distance. However, in areas with upstanding structures, especially those that have a significant dielectric contrast to their surroundings, interference from such surface objects can create artefacts on the radargram. When such isolated objects (powerlines, telegraph wires, metal poles, trees, windmills/waterpump structures) are passed during a traverse, a series of hyperbolae may be generated that appear like a subsurface object but are simply out-of-plane reflections. Radar antennas are commonly elongate, generating radar waves in a widening arc from their long axis. Thus when moved in parallel to the antenna axis, the radar waves may reflect from a larger subsurface area in front and behind the antenna, (the so-called footprint) than when moved with the antennas at right angles to survey direction. Antennas may be shielded with radio-wave attenuating materials that reduce such out-of-plane interference. Unlike other forms of electromagnetic radiation used in geophysics, radio waves have far higher rates of attenuation, and thus penetration and reflection depths are typically low, but horizontal accuracy is high, coupled with rapid, real-time results, unlike all other geophysical techniques bar metal detectors and magnetometer raw data. The receiving antenna has either electronic or fibre-optic link to a recorder that converts incoming radiowaves to digital format and displays these graphically as wavelets. As the transmitter-receiver array is moved, so these wavelets are stacked horizontally to produce a radargram, a kind of x-ray slice into the Earth, but recorded in the time taken for radar waves to penetrate and reflect, as opposed to real depth. The speed of radiowave propagation is determined by the makeup of the transmitting medium: in this case the speed of light and dielectric permittivity. Magnetic properties can also influence radar wave speed. Changes in dielectric permittivity can cause radar wave reflection, without which GPR profiling would be impossible. Radarwave attenuation, or signal loss is extreme in conductive media such as seawater, clays (especially hydrous) and some leachate. GPR has good depth penetration (tens to hundreds of metres) in ice (with minor fracturing/interstitial water), hard rocks like limestone and granite and clay-poor quartz silts or sands. Vertical resolution *vs.* depth penetration is of major concern when choosing antenna frequency. Low frequencies (15–50 MHz) achieve deep penetration with poor vertical resolution in the received signal, due to the long wavelength. High frequencies (500–1000 MHz) show high resolution with weak penetration (centimetres to metres). Low-frequency antennas are large (a few metres long), high frequency antenna are small (tens of centimetres). Again, this can influence the use of the method, as deeply buried targets in enclosed spaces are virtually impossible to survey.

As with all geophysical methods, some intelligence concerning the likely size and makeup of the target is useful: where unknown or questioned, then a range of antennas should be used, and in very poorly understood locations, with other geophysical and invasive techniques (Blunderbuss Approach). Moisture contents influence radar wave velocity because in homogenous media porosity has a direct relationship to dielectric permittivity. Thus dry sand will allow increased wave propagation: sand with high freshwater content will give improved vertical resolution. A problem with unshielded antenna is the effect of 'out-of-plane' reflections (see above, trees, poles), analysed by surveying the same line with different antenna orientations. It is easy to think of the radar wave as a focused beam (the ray-path at right-angles to the wave) when in fact the radar wave as it travels into the subsurface is more like a bubble, hemispherical at first, expanding and becoming distorted as it travels at different speeds into the ground. Thus lateral to the antenna, on or in the ground surface may be structures that cause reflections at ground level. The effect of these surface features can be diminished by altering the orientation of the antennas, or by shielding the above-ground portion of the antenna, such that the radio wave is only allowed to penetrate the ground. GPR has found it's best uses in imaging glaciers, sand deposits (river, non-saline coastal sands), aquifers (porous nature), archaeological features (moats, buried buildings) and concrete/pavements.