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<u>Communication and location under the ground: VLF technology tricks</u>

Trenchless Technology Overview

Construction: Laying Utilities, Pipelines, Cables

USA, Europe: AC heat pump systems, fiber optic cables

Big construction markets in India, China.

Trenchless technology *machinery* market: US$ 1 BLN per year.

Typical cost of the trenchless rig: $200,000.

The electronics is not so much constrained with the cost.

Problem: guidance of the drill head under the ground

Typical depth: 5m

Typical path length: 100m

Location accuracy: 10cm

Different methods were tried: acoustic, seismic, ground penetrating radar.

Most viable technology: VLF near field.

Technical challenges:

Dynamic range of the signal: 140dB (from 0.1uV to 1V at the receiver input)

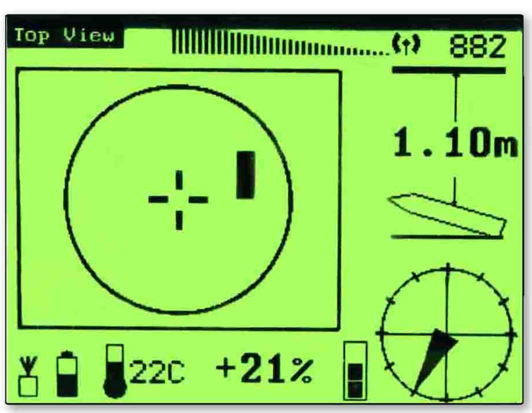
Telemetry information: roll, pitch, temperature, status; ~ few dozens bits per sec.

The telemetry is used for steering; this implies low latency communication. That rules out powerful coding schemes due to the unavoidable block delay.

Low data rate: there is enough of DSP processing power to apply optimal algorithms in the receiver.

Downhole transmitter: 3cm x 30cm, microcontroller based, battery powered.

Locator: handheld instrument, DSP based, battery powered.

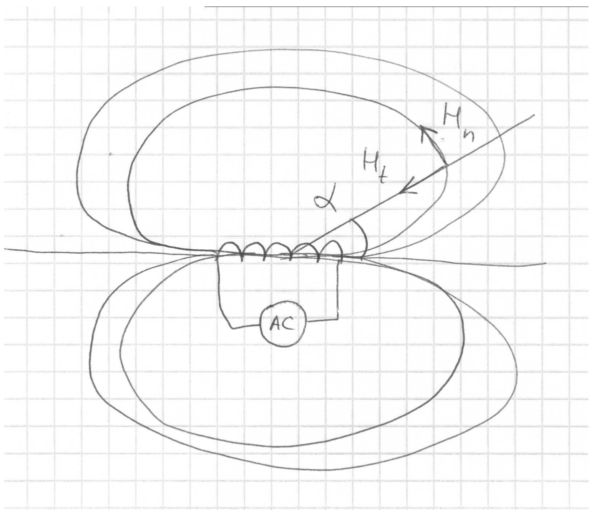


Typical view of the locator display

The VLF field in the ground

The VLF near field in the soil/air interface represents static magnetic problem (displacement currents are negligible). E field is shielded and could be assumed zero, ε and μ are equal to 1.

Textbook approximation of ideal dot magnetic dipole in the near field:



Normal and Tangential components of the H field:

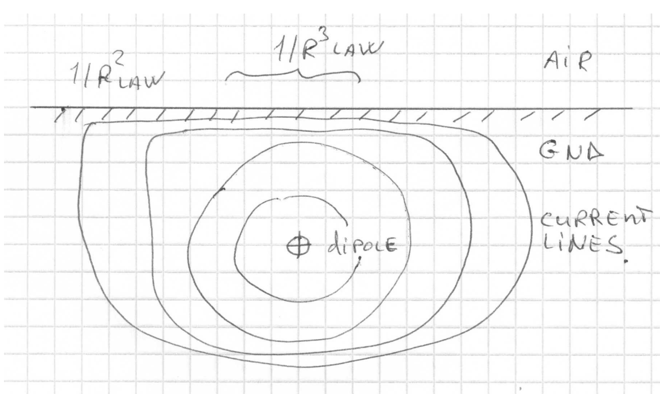
$$H_t = \frac{D}{R^3} 2\cos\alpha$$

$$H_n = \frac{D}{R^3} \sin\alpha$$

Module of H vector:

$$|H| = \frac{D}{R^3}\sqrt{3\cos^2\alpha + 1}$$

Dipole in conductive media:



Dipole field in the ground: eddy current flows along the interface surface to air. Finding a source by the field represents a difficult inverse electromagnetic problem. Numeric solution is possible.

Dipole radiation problem in conductive space was first considered by A. Sommerfield (1909). The problem received further treatment in the book of A. Banos (1966). However, the conclusions from books are not directly applicable to VLF near field locating problem.

Fortunately, the angular accuracy of location appears to be limited by the receive antenna alignment before the soil conductivity effects come into play.

It appears to be possible to apply approximation for the path loss:

$$|H| = \exp(-\Omega R)\frac{D}{R^3}\sqrt{3\cos^2\alpha + 1}$$

This approximation holds valid until the derivative of $\frac{1}{R^3}$ is lower then the derivative of $\exp(-\Omega R)$, so the geometric loss dominates over exponential part of the attenuation.

Path loss attenuation factor:

$$\Omega \sim \sqrt{\frac{\rho}{\omega}}$$

In this formula, ρ is the conductivity of the soil, and ω is the frequency.

The value of Ω is typically about 0.1 … 1 dB/m at 30 kHz, depending on the conductivity of the soil. Consequently, the geometric loss dominates over the attenuation at the distances of at least 20m, which is sufficient for our purpose.

Determining the position of the drill head transmitter

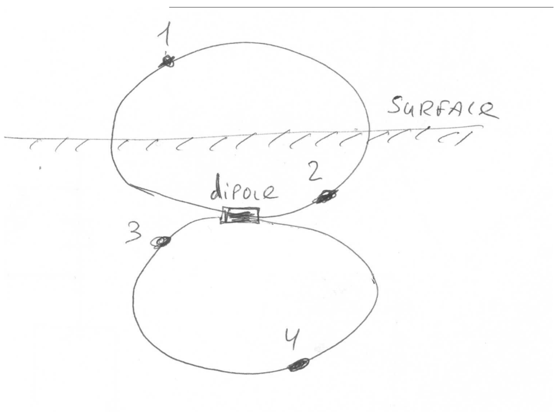
In order to locate the transmitter, we have to solve the system of equations:

$$H_t = \frac{D}{R^3} 2\cos\alpha$$

$$H_n = \frac{D}{R^3}\sin\alpha$$

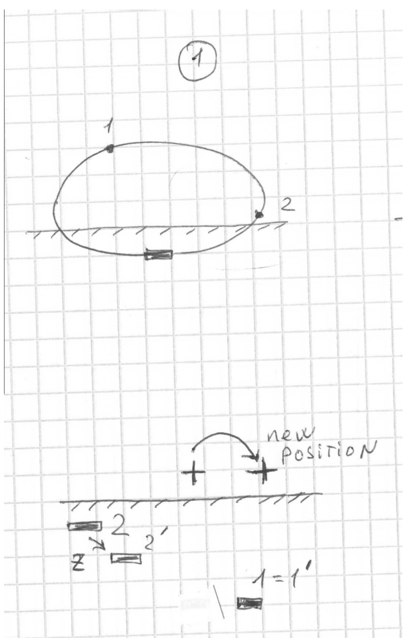
This system corresponds to the ideal dot dipole; we can correct the result for the soil conductivity later.

Solution of the system of equations is available in the closed form. Due to the symmetry of the dipole field, the system has 4 solutions in the general case.



The solutions #3 and #4 correspond to the location of the transmitter above the receiver, i.e. negative depth; those solutions can be eliminated. The remaining solutions #1 and #2 can't be resolved without additional information.

While the operator walks with the receiver, the magnetic field vector changes. We could resolve the ambiguity if we knew the coordinates of the operator when he is making the measurements. It could be possible to design in some navigation system to determine the coordinates of the operator; however it wouldn't be convenient from practical standpoint. So, we have to resort to a trick.



If we change the coordinate system from transmitter centered to receiver centered, then when the receiver moves in horizontal direction, the correct solution will remain at the constant depth, while the incorrect solution would seem to move in the vertical direction. This allows resolving which of the two solutions of the system of equations corresponds to the actual location of the transmitter. We don't need to know the coordinates of the receiver; all we have to do is compare vertical displacement versus the horizontal displacement for both solutions.

Optimal operating frequency

The operating frequency has to be selected so to maximize signal to noise ratio.

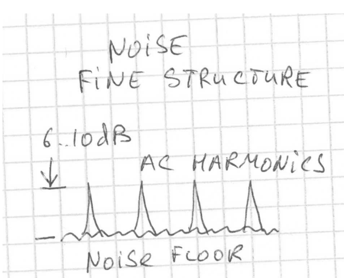
There is a lot of controversy about EM noise in the VLF bands in the literature; particular noise figure depends on area, weather, season and time of the day; big picture is hard to summarize. We had to do our own measurements for the parameters relevant for this application, i.e. the H field noise near the ground in the day time in construction season (spring – summer).

VLF noise consists of narrowband interferers, AC harmonics, pulses from atmospheric electric discharges, and wideband Gaussian noise component.

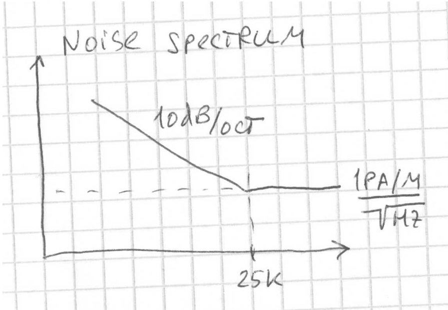
Narrowband interferers (VLF communications, standard frequency transmitters, traffic loops, SMPS and electronic ballasts, CRT scan harmonics, etc.) could happen at pretty arbitrary frequencies. The problem is that the most pronounced frequencies are different at every particular location; the generalization is hardly possible.

Atmospheric noise depends on local weather conditions. Even if there is no visible lightning activity, a cloudy sky is ~10dB noisier then clear sky. According to our observations, this noise component has essentially Gaussian distribution. This is different from usually assumed impulse nature of the atmospheric noise.

The impulse noise is caused by the nearby lightning discharges in the clouds and between the clouds and the surface. It consists of the wideband pulse bursts with the duration from tens to hundreds of milliseconds; the maximum of the noise spectrum is at several kHz.



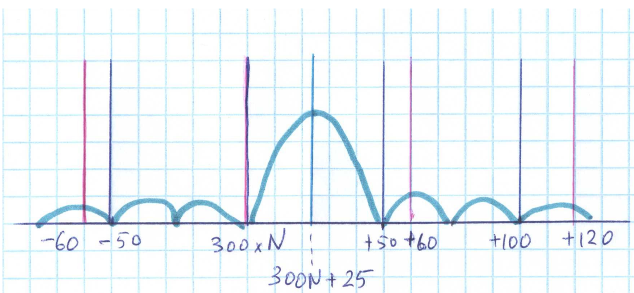
Everywhere but in the very rural areas the harmonics of the AC frequency prevail over the other types of noise by as much as 6…10dB.



The envelope of the noise spectrum (H component of the field) rolls down with the frequency with the rate about 10dB per octave, reaching relatively flat noise floor at about 25 kHz. The noise magnetic field strength density is at the order of $1pA/m/Hz^{1/2}$ at 30 KHz.

Considering losses in the ground and in the metal housing, and the ambient noise, the optimum carrier frequency appears to be about 30 kHz.

Since the power frequency harmonics are prevailing, it would be reasonable to select the operating frequency in the middle between the two adjacent AC harmonics. If the baud rate equals to half of the AC frequency, then the power harmonics will fall into nulls of the spectrum of the signal. That should allow for the ideal cancellation; however there is one difficulty: the utility frequency in Americas is 60 Hz, whereas it is 50 Hz in the rest of the World. In Japan, they use both 50 Hz and 60 Hz utilities.



We selected the operating frequency according to the formula:

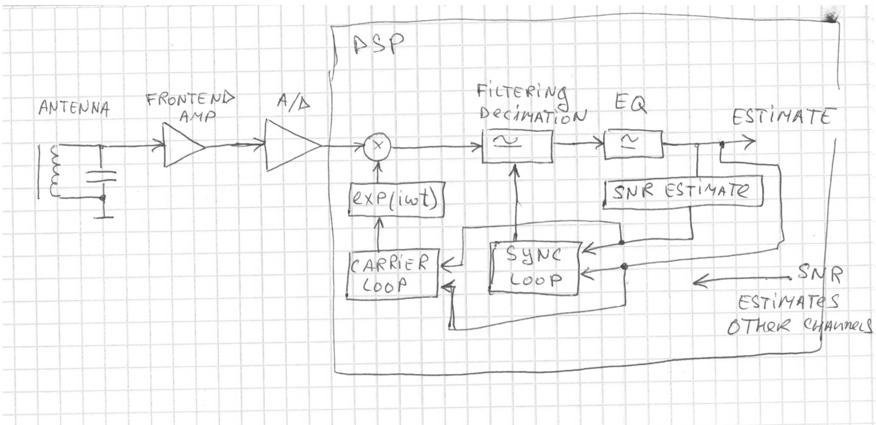
$$F = 300 \cdot N \pm 25Hz$$

The 300 Hz is the least common multiple of 50 Hz and 60 Hz; the selection of the carrier frequency in +/- 25 Hz away from the common multiple, and the baud rate of 25 symbols/sec places the nearest null of the signal spectrum at harmonic frequency for both 50 and 60 Hz. For 50 Hz interference, the cancellation is perfect for all harmonics. For 60 Hz, the nearest harmonic is suppressed perfectly, and the next harmonics fall into the excess bandwidth of the signal, so they could be filtered out without much difficulty.

The last step was choosing such N so the optimal carrier frequency could be divided from standard general purpose crystal frequencies. For that reason, we selected the carrier frequency of 30,875 Hz (very close to that frequency could be obtained from 6.144 MHz standard crystal divided by the ratio of 199).

Receiver Design

The receiver was built using Analog Devices BlackFin^{tm} DSP.



The analog frontend with adjustable gain accommodates for the 140dB of the dynamic range of the signal. The minimum signal strength is approximately -155dBm. The input signal is directly sampled by an ADC at 96 kHz, and decimated to lower processing rate. The total computing needs are approximately 130 MIPS; the majority of the processing is taken by the decimation filters. The coherent demodulators are employed. The carrier and symbol synchronization operates from the decision directed loops with the optimal control algorithms.

Fast Acquisition

Classic PLL approaches like loops with Costas carrier phase detector and Gardner symbol timing detector require significant amount of averaging (~hundreds of symbols) to achieve good lock; so the implementation losses due to the imperfect synchronization will be under 1dB. When operating at the baud rate of 25 symbols/sec, the PLL pull-in time appears to be at the order of 10 sec; that would be inconvenient for the operator. We used optimal control algorithms instead of the classic linear filters; that reduced the acquisition time by an order of magnitude in conditions of high SNR. The adaptive filter operates on the current SNR estimate and the phase error estimate. The receiver processes the signal from three magnetic antennas, corresponding to three orthogonal components of the field. Those signals are fed into carrier and symbol sync loops, as well as into the telemetry receiver algorithm.

Optimal phase lock loop:

1. Get the current estimate of phase error and frequency error
2. Get the accuracy of the phase and frequency estimates
3. Adjust the loop filter so the accuracy of the estimates is ~3 times better then the current estimates.
4. Generate the loop output so to compensate the current error precisely within one sample interval.

Result: the pull-in is faster by an order of magnitude compared to an ordinary PLL.

Questions?

Literature:

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