The Volterra Acquisition System: a multi-sensor system

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ABSTRACT

The Volterra Acquisition System is a highly flexible distributed acquisition system capable of acquiring data from many different sensors. Development was motivated by the limitations in commercial induced polarization systems of the early 2000's. Beginning with a desire to build a better IP system, continuous research and development over 16 years has resulted in a fully featured, multi-sensor, universal acquisition system capable of both surface and borehole surveys. The Volterra system consists of independent, four channel, full-waveform data acquisition units and advanced signal processing software.

INTRODUCTION

The Volterra Acquisition System is a highly flexible distributed acquisition system capable of acquiring data from many different sensors. Induced polarization (IP), electromagnetic (EM), controlled-source electromagnetic (CSAMT) and magnetotelluric (MT) surveys have been successfully completed with the Volterra system. At its core, the system consists of data acquisition units and advanced signal processing software. The independent, four channel, 24-bit, full-waveform data acquisition units have industry-leading flexibility enabling the execution of advanced survey designs.

MOTIVATION

The motivation for the development of a new acquisition system was a direct response to the limitations of commercial induced polarization systems available in the early 2000's. Most systems lacked flexibility and made innovation difficult. Acquisition was limited to preprogrammed standard array definitions including Dipole-Dipole, Pole-Dipole, Pole-Pole, Gradient, and Wenner arrays, etc. Receiver units required common poles between adjacent dipoles; this configuration was hardwired in the electronics. Common to all commercial systems at the time was a lack of information about how the instrument processed the raw data collected. Effectively, these were black boxes where only the manufacturer had knowledge of the signal processing being carried out. Developing a new acquisition system was the best way to overcome these limitations.

Increased computer power and the availability of 3D inversion algorithms dramatically altered what could be done with IP data processing and interpretation. The commercial systems available at the time lacked the flexibility to take advantage of these new developments. The increase in computer power meant that the general apparent resistivity equation could be utilized rather than the simplified equations for specific array geometries. The ability to invert data in 3D led to experimentation with new array designs and 3D acquisition techniques that could better take advantage of the new modelling capabilities. These changes reinforced the need for a better and more modern IP system.

DEVELOPMENT

The Volterra System is the result of significant hardware and software development over the past 16 years. Development came as a series of steps with each making significant improvements over the predecessor. The initial focus was induced polarization surveys. As the hardware became more advanced electromagnetic surveys increased in importance and together both surveys drove development. Throughout, SJ Geophysics has embraced the principle of creating a universal acquisition unit capable of being deployed with any sensor.

SJ Geophysics' first acquisition system, released in 2004, was the SJ-24. It was a 16-channel, tethered, full-waveform acquisition system with a computer for raw data storage and real-time signal processing. Multiple 4-channel units were connected together to achieve the 16 channels. In theory, greater channel counts were possible, but in practice was limited due to data transfer rates and communication bottlenecks. Numerous SJ-24 surveys have been completed since its release in a wide variety of environments and in multiple countries. Although an improvement over commercial systems, there were notable limitations. The channel count was effectively limited to 16-channels and multi-conductor cables often experienced cross-talk in wet and cold (~0 °C) environments.

In 2010 SJ Geophysics released Volterra-IP, their first distributed acquisition system. It consists of individual, single channel, full-waveform data acquisition units with internal flash memory data storage. The maximum sampling rate is approximately 7 kHz restricting their use to IP and MT. The number of data acquisition units that could be deployed simultaneously was limited only by logistics and crew size. Data processing was carried out nightly on a processing computer.

In 2013 SJ Geophysics' Volterra distributed acquisition system was significantly improved. The data acquisition units were re-designed to be lighter, require less power, and have higher signal-to-noise ratios compared to the previous single channel units. The new units contained four full-waveform channels capable of sampling rates up to 128 kHz. Significant signal processing software improvements were also made. With the increased sample rate and new software, electromagnetic data collection became possible. The design of the electronics also allowed the units to be inserted into the narrow space of a borehole probe. This was the starting point for the Volterra system currently in use today.

The process of constant improvement is the basis for the Volterra acquisition system. Driven by the principal of universal acquisition, it has evolved into a multi-sensor, highly flexible, distributed acquisition system capable of a wide spectrum of geophysical surveys including IP, EM, MT, CSAMT, and MMR/MIP.

VOLTERRA ACQUISITION SYSTEM

The Volterra Acquisition System consists of two core parts; data acquisition units and a standalone advanced signal processing software package. As a distributed acquisition system the signal output from the attached sensor is measured, digitized, and stored within the acquisition unit on internal flash memory. The stored data is downloaded at the end of each survey day via USB to a laptop computer where it can be processed and the geophysical parameters calculated.

Surveys acquired with the Volterra system include 2D/3D IP, EM, MT, and CSAMT. Other source and sensor combinations are possible. The most common sensors utilized by the Volterra system today are:

- Stainless steel electrodes and porous pot electrodes
- Highly sensitive B-field induction coils
- 3-component Fluxgate magnetometers

Figure 1: Volterra borehole probe in Northern Saskatchewan. Multiple sections consisting of data acquisition units, battery pack, B-field coil, and 3-component fluxgate magnetometer.

Data Acquisition Hardware

The form factor for the Volterra data acquisition units was inspired by the unique challenges associated with the steep and rugged mountainous terrain of British Columbia, Canada. For both IP and EM surveys, having lightweight and portable instruments is important as it enables field crews to access challenging terrain efficiently and safely. The surface acquisition units, shown in Figure 1, weigh approximately 1.25 kg including battery.

Figure 1: Volterra acquisition unit (surface) with battery pack. Approximate size is 40.5 cm long and 43 mm in diameter

The design of the circuit boards was influenced by the desire to create a borehole probe. Elongated, rectangular boards were chosen to fit within a borehole probe form factor. The Volterra borehole probe (Figure 2) was designed in-house and is capable of surveying to depths of 3000 m. Both 38 mm and 32 mm diameter probes have been designed.

The data acquisition units are controlled using Bluetooth wireless communication from Android devices running custom apps. All aspects of the data acquisition units can be controlled, including start/stop of recording, instrument integrity checks, and viewing of live data streams.

Each independent data acquisition unit acquires full-waveform data from 4 galvanically-isolated fully differential input channels. The sampling rate of the data acquisition unit is set by the operator and can vary from 1 kHz to 128 kHz. Each acquisition unit has an input impedance of 100 MΩ and 32 GB of internal flash memory for storage of the raw data.

Any electronic system has noise associated with it no matter how well it is built. The maximum signal-to-noise that can be achieved in a perfect system is ~124 dB (Triggs, 2016) which corresponds to approximately 21-bits; the remaining bits are lost in unavoidable circuit noise. Therefore, using a 24-bit ADC for digitizing is more than sufficient. In the Volterra system, signals on each channel are measured with a 24-bit ADC that has an intrinsic sampling rate of 128 kHz. We have directly measured approximately 5½ bits are lost due to noise in the system at 128 kHz sampling rate.

Lowering the sampling rate can increase the number of effective bits (ENOB) as individual samples are averaged together through the use of a filter (Kester, 2009). For example, in a boxcar filter all the samples are evenly weighted and the number of effective bits is increased as the square root of the number of taps in the filter. This is assuming a simple noise model where the noise is roughly uniform and its amplitude is such that it toggles the ADC output.

The Volterra digitizer can be configured to sample at lower rates: 64 kHz, 32 kHz, and so on by factors of 2, down to a rate of 1 kHz. In the case where a sampling rate is chosen to be less than the 128 kHz maximum, the rate from the ADC is reduced in the firmware by a combination of 2x and 4x finite impulse response (FIR) filters. The FIR filter taps give each sample that is inputted to the filter a different weight. Most of the weighting is over a small number of samples. Taking this into account, and using a simple noise model, each time the 2x filter is applied we estimate that we get 0.55 additional effective bits, and each time the 4x filter is applied 1.09 additional effective bits are realized. For the possible sampling rates of the Volterra system, the number of effective bits are given in Table 1 and compared to a state-of-the-art Texas Instruments 32-bit ADC (Texas Instruments, 2015).

Sampling Rate (Hz)	Volterra 24-bit ADC Effective Bits	TI ADS126x 32-bit ADC Effective Bits
128,000	18.5	-
64,000	19.1	-
38,400	-	15.6
32,000	19.6	-
19,200	-	20.1
16,000	20.1	-
14,400	-	20.6
8000	20.7	-
4800	-	21.4
4000	21.2	-
2400	-	21.9
2000	21.8	-
1200	-	22.5
1000	22.3	-
100	-	24.2
10	-	25.9

Table 1: Comparison of the effective number of bits between the Volterra 24-bit ADC and the TI ADS126x 32-bit ADC.

Besides increasing the ENOB of the system, reducing the sampling rate has other benefits: it saves space on the on-board memory, and keeps data files small for subsequent processing. The smallest sampling rate that is practical for a given application is usually chosen. For example, TEM applications might use a sampling rate of 32 or 64 kHz while 2 or 4 kHz would be more appropriate for IP signals.

User selectable gains were developed for the front end of each acquisition unit. There is a wide range of instrumentation that can be used in conjunction with the data acquisition units. Each of these sensors has its own range of output which may be large or small in comparison with the input range of the ADC (±5 V). Gain programmability overcomes this problem because it allows one to maximize the number of the useful ADC bits with which the signal is digitized. Another situation where programmable gains are useful is when signal strength varies over the course of a survey. For example, when a sensor gets close to a source, reducing the gain can prevent the data acquisition unit signal from going beyond the maximum allowed value on the ADC.

There are 4 serial ports and 6 digital I/O (DIO) ports available for connecting peripherals to the data acquisition units. One commonly connected device is a GPS unit which is critical for precise timing across the system. Other uses for these ports are frequency counting, timestamp applications, on/off signal control, etc. Data from inertial measurement units (IMU) are also recorded. The borehole probe has additional IMU and temperature sensors.

Calibrations are typically provided by the manufacturers of the various sensors. Often, these calibrations do not take into account the small differences between individual instruments of the same model. High-precision calibration measurements across the full bandwidth for each sensor are done in-house. The results are used in the data processing stage. Regular calibration of our instruments also allows us to monitor possible changes in response over time.

The Volterra acquisition units have been designed to be capable of acquiring any type of data within the system's frequency and voltage range making it a true multi-sensor system.

Signal Processing Software

The signal processing software for the Volterra Acquisition System is called *Controlled Source Processing* (CSProc). CSProc is written in Python and makes use of open-source scientific computing libraries including SciPy and NumPy (Langtangen, 2014). The software is run on PCs using the Linux operating system. CSProc handles the raw full-waveform data and trims, filters, stacks, and calculates the geophysical parameters.

A big advantage of full-waveform data is that data processing occurs after the data is collected. Multiple processing runs can be used to extract different information from the same raw data. Examples include, combined IP/MT surveys where data is processed once for IP and a second time for MT, or borehole EM surveys where the total magnetic field is collected simultaneously with the EM data. The collection and storage of full-waveform data enables survey results to be reprocessed in the future if, for example, improved signal processing algorithms are developed.

CSProc is able to process data collected using both 50% and 100% duty cycle transmitters. For all controlled source surveys the transmitter waveform is recorded using a current monitor. The transmitter waveform is utilized during processing for all survey types. The same type of data acquisition units measure the source signal and the response at each sensor.

The collection of high-quality EM data requires a stable transmitter waveform. SJ Geophysics developed an EM transmitter in-house to gain complete control over waveform generation and ensure precision timing. The EMTX is capable of arbitrary duty cycle waveforms and a wide range of base frequencies from 0 Hz to 8 kHz.

The use of 100% duty cycle waveforms have a number of advantages over 50% duty cycle waveforms. The main advantage is one can record twice as many stacks in the same amount of time at twice the transmitter frequency. The second advantage is that the amplitude of the measured signal is doubled. These are illustrated in Figure 3. For example, in 100% duty cycle IP the signal-to-noise ratio is increased by a factor of two, prior to normalization, as the measured on-time chargeability is the sum of the off-time chargeability decay and the on-time chargeability build up (Olsson, 2015).

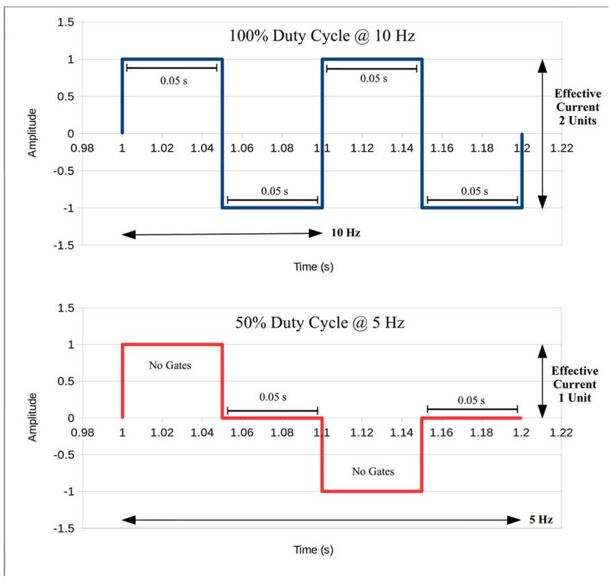

Figure 1: Comparison between 100% duty cycle and 50% duty cycle transmitter waveforms.

In many EM surveys, data is acquired at the same stations from multiple loops. CSProc is capable of acquiring data from multiple transmitter loops simultaneously. This requires that the base frequencies of the transmitter waveforms for each loop have different harmonics. During processing the data corresponding to each loop is separated using filtering techniques and processed as usual.

As discussed, the Volterra hardware is generalized and is not specific to a single survey type. It is CSProc that controls how the full-waveform data should be processed. For example, the acquisition of combined IP and MT data is the same from the viewpoint of the data acquisition unit, but during processing different workflows are applied to the raw data.

CONCLUSION

The Volterra acquisition system is a highly flexible, multi-sensor, distributed acquisition system. Developed as a result of limitations in commercial induced polarization systems it has grown into a fully featured acquisition system following the principal of universal acquisition.

The biggest difference between Volterra and other distributed acquisition systems is flexibility. There are no requirements to follow specific survey configurations as is often the case with other systems. Survey parameters are easily adjusted to customize the survey design to the specific needs of the exploration objective. For IP this includes line spacing, array configuration, dipole size, number of active channels, 2D, 3D, etc. For EM this includes the measured components (x, y, z), the number of acquisition units active, type of sensor, transmitter waveform, base frequency, etc.

Constant improvement has been a big factor in the development of the Volterra acquisition system and has enabled it to become what it is today. This will continue to be a driver for system development in the coming years.

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