PRECISION SIP MEASUREMENT SYSTEM FOR LABORATORY USAGE

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Abstract

IP or complex measurement of core sample or water with pollution is very important for exploration geophysics, engineering geophysics and environment geophysics. Current SIP measurement system for laboratory usage can work well for sample with high DC resistance because of using amplifier with high impedance as input buffer. But its inherent noise is high, and the precision of SIP measurement is poor when it measures the SIP of sample with low DC resistance. The situation is worse especially for environment problem when the resistance of water sample with high pollution is very low. Our development is to design and realize a precision SIP measurement system suitable to sample with very high resistance and very low resistance. We design three input buffers in a single board with switch option corresponding to low resistance, medium resistance, and high resistance of different sample. An ultra-low noise buffer with voltage noise as low as 1 nV/sqrt(Hz) is adopted for sample with low resistance (≤ 1000 Ω). An ultra-high input impedance buffer is adopted for sample with high resistance (≥ 1 MΩ). A general input buffer is adopted for sample with medium resistance (< 1000 Ω & < 1MΩ). Each buffer is composed of 4 channels to measure current and voltage with differential input. Active shielding is used for each channel to prevent parasitic capacitance among measurement wires. A high precision data acquisition system with 4 channels is also developed. The data acquisition system is optimized for geophysical signal acquisition with frequency range from DC to 1000Hz. The calibration and compensation process are adopted to reduce measurement error. We tested our system on resistors with resistance as 0.1Ω, 1Ω, 10 Ω, 100 Ω, 1.2 KΩ, 10 KΩ, 100 KΩ, and 930 KΩ in frequency 1 Hz ~ 800 Hz, and the measurement error is less than 0.1 mrad. We also carried out a test on core samples with low resistance, high resistance, and medium resistance, the measure error was less than 0.1 mrad in most conditions.

Introduction

SIP is a promising tool in discrimination IP anomaly caused by economic mineral and non-economic mineral. It is also a potential tool for water searching and the evaluation of environment problems. Therefore, the measurement of SIP of samples in laboratory is very important. The phase shift caused SIP phenomenon is usually less than 1° or 17.45 mrad. The error of SIP measurement should be less than 0.01° or 0.17 mrad. It's a challenging task when the DC resistance of sample is small (< 10 Ω) or very big (>10 MΩ). Zimmermann et al. (2008, 2010) quantifies the systematic errors caused in measurement system and find a method to correct some of these errors. But practice shows that random errors at low frequency (1m Hz ~ 0.1 Hz) are still a serious problem. And the systematic errors is still a problem when the resistance of sample is great than 10 MΩ.

To solve above problem, we design a new buffer and adopts a data acquisition system specially designed for geophysical data acquisition with the removal of 1/f noise.

Error Sources in SIP Measurement

The error sources in SIP measurement can be classified as systematic error and random error. Zimmermann et al. (2008) gave a detailed description of systematic errors in SIP measurement. In this paper, we will analysis random error in SIP measurement in detail, and consider some systematic error not covered by Zimmermann et al. (2008).

Systematic Error Sources

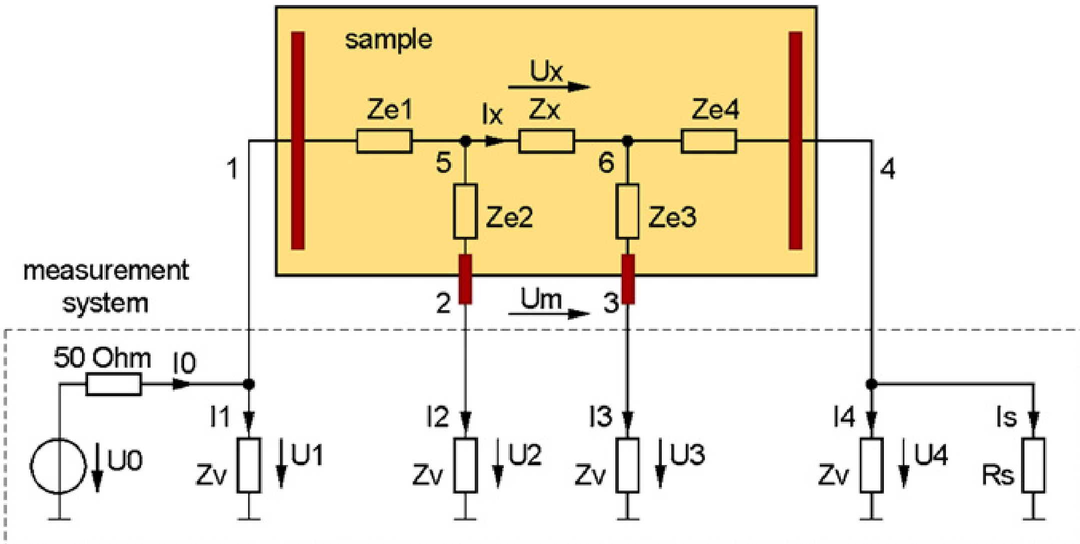

Figure 1: Simplified electrical model of the sample and the measurement system (from Zimmermann et al. 2008)

We follow the model for SIP measurement (Figure) by Zimmermann et al. The systematic error of ***Ix*** which flows into sample is caused by leakage current ***I3*** and ***I4***. Leakage current ***I3*** and ***I4*** are determined by the input impedance of buffer which is equal to input resistance parallel to input capacitance. There exist a dilemma for the selection of input resistance and input capacitance. The voltage noise is big for a buffer with large input impedance. The low noise buffer is suffered from relative small input impedance. The input impedance of the buffer also affects the accuracy of the measurement of potential difference between potential electrodes. Increasing the impedance of the buffer will decrease the error of potential measurement. But the increasing of the impedance of a buffer will increase voltage noise of the buffer.

Zimmermann et al. (2008) chooses amplifier AD JFET OP AD825 for the buffer. The AD825's impedance is not enough for sample with high resistance (> 10 MΩ). And it's voltage noise is large when the measurement frequency is less than 10 Hz.

Random Error Sources

The random error sources in a buffer or voltage follower can be expressed as following.

$$E_{ni}^2 = E_t^2 + E_n^2 + I_n^2 R_s^2 \quad (1)$$

Where *Et* is the thermal noise of the sample under measurement which is proportional to resistance *Rs* of the sample, *En* is the voltage noise of an amplifier, and *InRs* is the noise caused by current noise of the amplifier which is multiplied by *Rs*. When *Rs* is small (e.g. < 100 Ω), the voltage noise of an amplifier is great than the thermal noise of *Rs*. The AD825's voltage noise is roughly equal to the thermal noise caused by a 5 kΩ resistor. When *Rs* is big (e.g. > 10 MΩ) , the current noise of a amplifier will be the dominant noise sources.

We will give a detailed comparison of output voltage noise by simulation in the following section.

The noise of data acquisition system is also very important factor when the measurement frequency is less than 10 Hz, because ordinary data acquisition system is often suffered from 1/f noise. The data acquisition card NI4472, which is used by Zimmermann et al. (2008), also faced the problem of 1/f noise. It's input noise is about 100 nV/sqrt(Hz) at frequency 1 KHz, and increase to about 1300 nV/sqrt(Hz) at frequency 1 Hz.

Precision SIP Measurement System

Our practice shows that the resistance of sample for SIP measurement owns great range of variation from 10 Ω to 1 GΩ (= 1000 MΩ). The sample of igneous rock often owns large resistance. The resistance of clay sample is often small. So it is impossible to use one buffer to satisfy the measurement requirement.

Precision Buffers for Ultra-high Impedance Sources and Ultra-low Impedance Sources

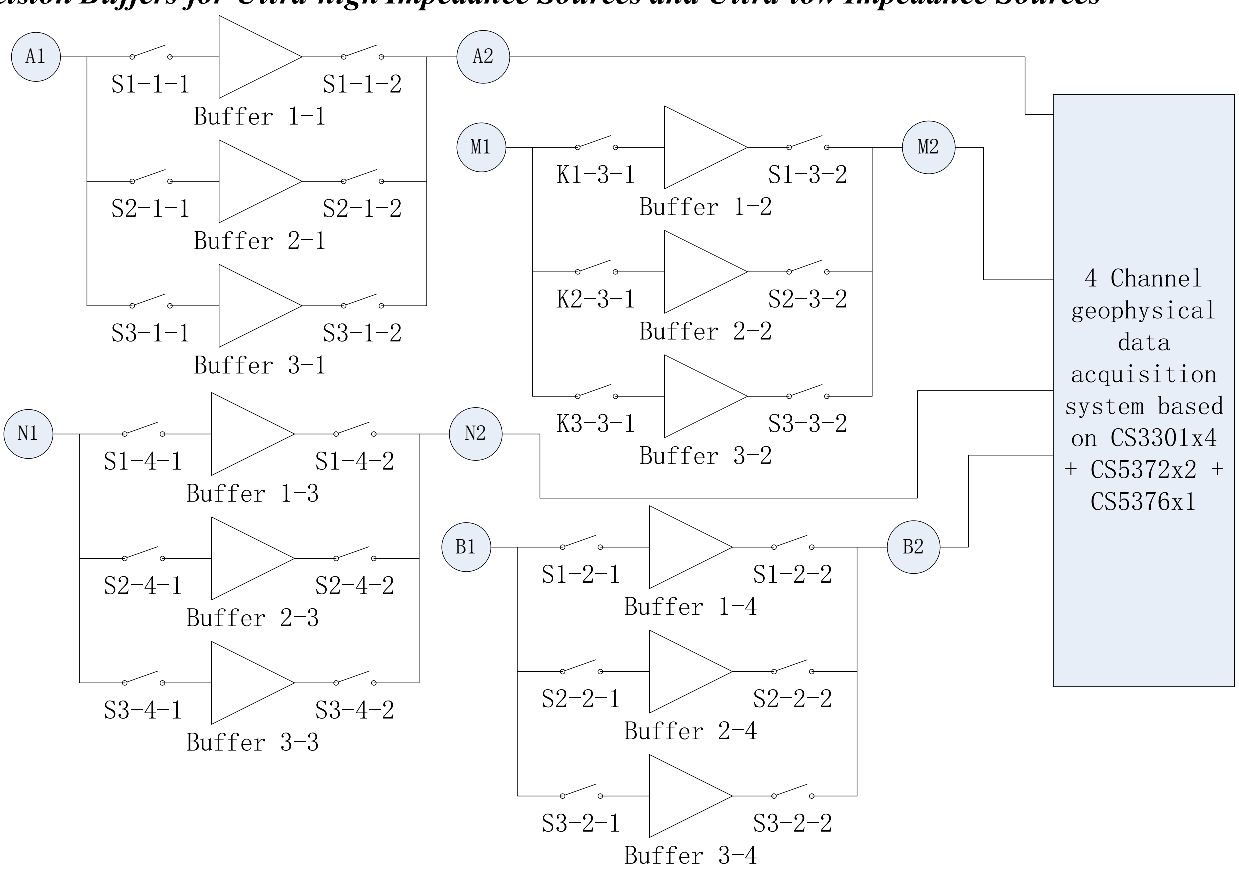

Figure 2: Scheme of precision buffers and data acquisition system for SIP measurement

Figure 2 shows our scheme for precision SIP measurement in laboratory. We use three carefully designed buffers to satisfy great range of resistance of sample. Amplifiers ADA4898, OPA827, and AD549L are selected for our design. Table 1 shows parameter comparison of amplifiers used for our design and Zimmermann et al. (2008). ADA4898 is selected for sample with resistance less than 1 KΩ. It's input voltage noise is 0.9 nV/sqrt(Hz) and input capacitance is 3.2pF. OPA827 is selected for sample with resistance range from 1KΩ to 1 MΩ. It's input voltage is only 4 nV/sqrt(Hz), and input current noise is only 2.2 fA/sqrt(Hz). It's a better choice than AD825. AD549L owns ultra-low input capacitance, ultra-low input current noise and the biggest input resistance. It's the best choice for sample with resistance great than 1 MΩ.

Table 1: Parameter comparison of amplifiers used for buffers

Op Amp	Input Voltage Noise	Input Current Noise	Common Mode Input Resistance	Common Mode Input Capacitance
ADA4898	$0.9nV/\sqrt{Hz}$ f=1kHz	$2.4pA/\sqrt{Hz}$ f=1kHz	30 MΩ	3.2 pF
OPA827	$4nV/\sqrt{Hz}$ f=1kHz	$2.2fA/\sqrt{Hz}$ f=1kHz	$10^{13}\Omega$	9 pF
AD549L	$35nV/\sqrt{Hz}$ f=1kHz	$0.11fA/\sqrt{Hz}$ f=1kHz	$10^{15}\Omega$	0.8 pF
AD825	$12nV/\sqrt{Hz}$ f=10kHz	$10fA/\sqrt{Hz}$ f=10kHz	$5\times10^{11}\Omega$	6 pF

Precision Data Acquisition System Without 1/f Noise

The data acquisition system uses the same idea adopted in seismic data acquisition system. Chopper amplifier CS3301 which remove *1/f* noise is used. 24-bit ADC package CS5372+CS5376 which is specially designed for geophysical data acquisition is adopted for our design. Chen et al. (2010) achieved ultra-low noise performance by using above amplifier and 24-bit ADC in electromagnetic exploration system. The same design was used in large-scale SIP exploration system and proved by field exploration (Xi et al., 2013, 2014).

Simulation of Random Noise in SIP Measurement System

There are well defined pSpice model and tools in simulation of current noise and voltage noise for circuit based on operational amplifier. We developed simulation model based our design and measuring procedure of SIP. The performance of our design can be simulated with high precision.

Simulation Model

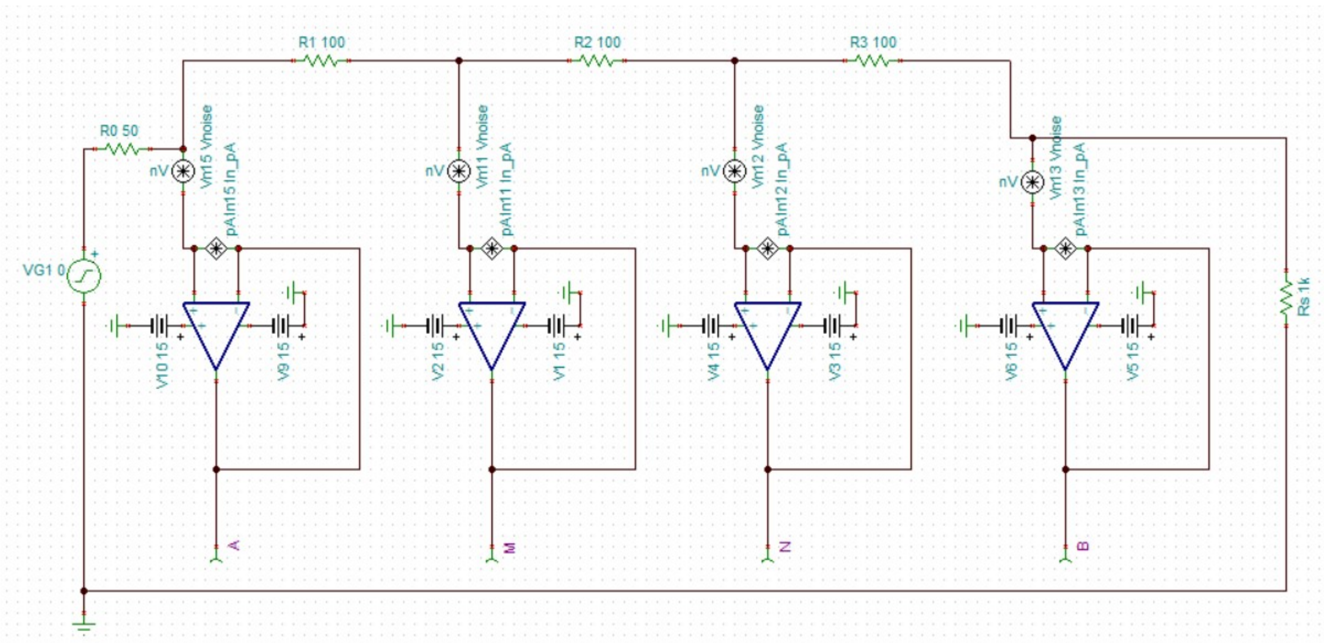

Figure 3: Simulation model of random noise in SIP measurement

Figure 3 shows simulation model for rand noise in SIP measurement. R1, R2, are R3 are resistance of sample in different part. Rs is used for sensing the current. A, M, N and B present the output of buffers with its input as current electrodes and potential electrodes connected to the sample. We change the type of amplifier and the value of R1, R2, R3, Rs to simulate different situation.

Simulation Result and Analysis

Table 2: Output voltage noise of buffers

OP AMP	**Output Noise of buffers R1 = R2 =R3 = Rs = 1Ω**			
	A	**M**	**N**	**B**
AD549	1.42 μ V	1.42 μ V	1.42 μ V	1.42 μ V
OPA827	137.99nV	138.04nV	138.1nV	138.15nV
ADA4898	51.88nV	52.05nV	52.22nV	52.37nV
AD825	1.97 μ V	1.97 μ V	1.97 μ V	1.97 μ V

Table 2 shows output voltage noise of each buffer when the resistance of sample is 1Ω. It's clear the noise of ADA4898 is the lowest. The amplifier's voltage noise is dominant when the resistance of sample is small. So it is very important to use low-noise amplifier for small resistance of sample.

The noise of each buffer is almost equal when R1, R2, R3 and Rs are equal. Therefor we just analyze the variation of noise voltage of M for different resistance of sample.

Table 3 shows the noise voltage when the resistance increases. ADA4898 should not be used for resistance of sample great than 10 kΩ. OPA827 is best for resistance of sample range from 10 kΩ to 1MΩ.

Table 3: Voltage noise for different resistance of sample

OP AMP	10kΩ	100kΩ	1MΩ	10MΩ
AD549	1.45 μ V	1.72 μ V	3.61 μ V	10.6 μ V
OPA827	361.83nV	1.06 μ V	3.33 μ V	10.62 μ V
ADA4898	925.73nV	8.45 μ V	83.72 μ V	836.0 μ V
AD825	1.99 μ V	2.23 μ V	3.87 μ V	10.9 μ V

Prototype of Precision SIP Measurement System

We developed a prototype for precision SIP measurement system to verify the result of simulation and make practical measurement.

Precision Buffers

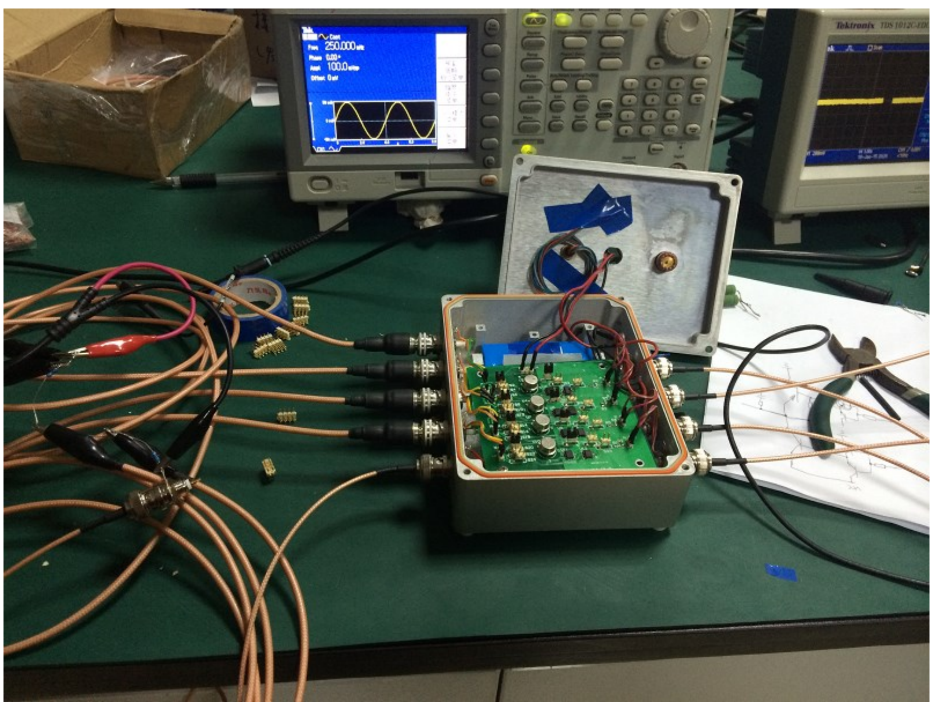

Figure 4: Prototype of precision buffers

As shown in figure 4, triaxial cables are adopted for connection to electrodes. Coaxial cable are used for connection to data acquisition system. The buffers is installed in a metal box and is powered by rechargeable battery to prevent power line noise and electromagnetic interference.

Precision 4-channel Data Acquisition System

The data acquisition system is modified for data acquisition unit for SIP exploration (Xi et al., 2014). It supports wired network and wireless network. The data acquisition software is installed on personal computer or PDA. The result is shown in PC or PDA with wired connection to 4-channel data acquisition system (Figure 5).

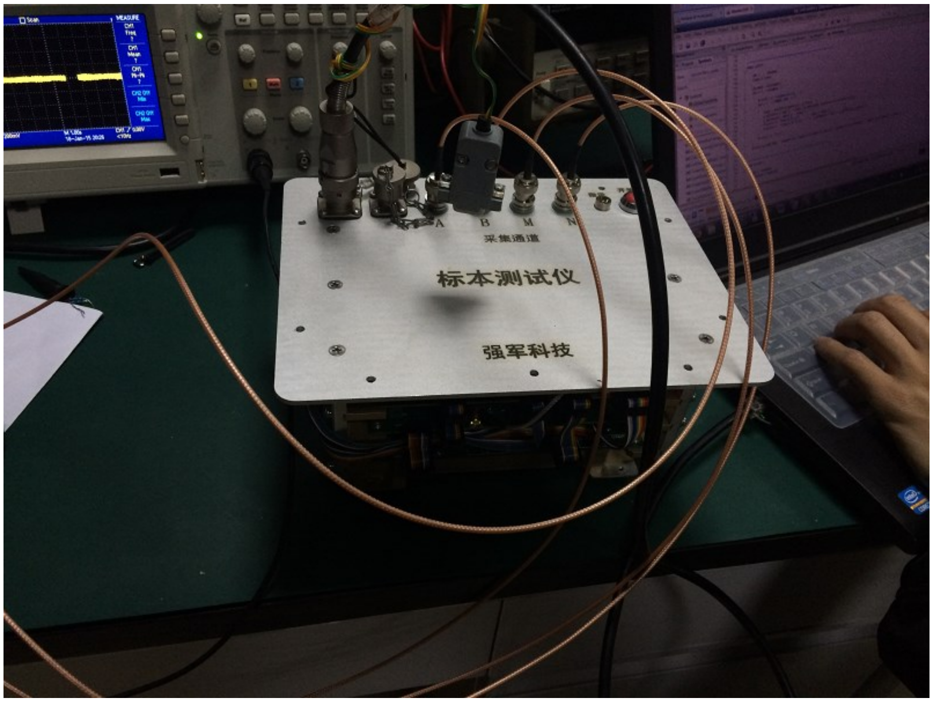

Figure 5: Data acquisition system

Test of SIP measurement system

We test our design by well-defined resistors (Figure 3) and samples, and compared the result to measurement result by other instrument. Tektronix AFG3021C signal generator is used for current source, and we use rectangular wave as excitation to improve test efficiency. At most conditions, we can use up to 21 harmonics with phase uncertainty less than 0.5 mrad for all harmonics. The phase accuracy will increase if pseudo random signal is applied.

Testing by Resistors

We use HIOKI 3522-50 LCR HiTESTER and SIP measurement system (SIP tester) to make the amplitude and phase measurement at frequency as 1 Hz, 8 Hz, 128 Hz, and 800 Hz for 0.1Ω, 1Ω, 10 Ω, 100 Ω, 1.2 KΩ, 10 KΩ, 100 KΩ, and 930 MΩ resistors as precision as 1%. We find that we can make phase measurement at high accuracy, but the uncertainty of the amplitude will be about 5% for resistance as 0.1Ω. For resistance of 1 KΩ or more, the uncertainty of amplitude will be less than 1%. Table 4 shows testing result of 1% resistors by 3522-50 LCR and SIP tester. The phase precision of SIP tester is much high than that of 3522-50 LCR because of high precision data acquisition system inside SIP tester which can remove *1/f* noise.

Table 4: Complex resistance of resistors at 1 Hz measured by 3522-50 LCR and SIP tester

Rated Resistance	3522-50 LCR		SIP Tester	
	Resistance (Ω)	Phase (mrad)	Resistance (Ω)	Phase (mrad)
0.1Ω	0.1012	-1.57	0.1052	-0.59
1Ω	0.9985	-0.87	0.9990	-0.12
10Ω	10.003	-0.69	10.01	-0.02
100Ω	100.13	-0.69	99.92	-0.01
1.2kΩ	1.202k	-0.69	1.203k	-0.01
10kΩ	10.006k	-0.69	10.06k	-0.01
100kΩ	100.17k	-0.34	99.87k	-0.02
930kΩ	929.60k	-1.04	925.6k	0.01

Testing by Typical Rock and Ore Samples

Seven samples including sedimentary rock, igneous rock and ore are tested. Theses samples are also tested by a time-domain IP tester SCIP for core sample. Same sample holder is used for testing, and the photo of samples and holder is shown in figure 6 & figure 7.

Figure 6: Samples and sample holder for IP testing

SCIP can only do time-domain IP measurement. To compare with the measurement by SCIP, we list the data of resistance of sample in 1/8 Hz and percent frequency effect (PFE) between 1/8 Hz and 9/8 Hz. Table 5 shows the result of comparison. We just list typical result here. For sample KQ017-B, the resistance measured by SCIP and SIP tester is 104 Ω and 207Ω, this difference may be caused by sample holder. For sample 616-86-10, the resistance measured by SCIP is less than that of SIP tester, this difference may be caused by leakage current inside SCIP. For sample N210-62-6, we find a very big difference in resistance measured by SCIP and SIP tester. This difference should be caused by leakage current inside SCIP. This comparison shows that the leakage current is big problem in traditional IP measuring instrument.

Table 5: IP measurement by SCIP and SIP Tester

Sample No.	Sample Description	SCIP		SIP Tester	
		Resistance (Ω)	Chargeability (%)	Resistance (Ω)	PFE (%)
KQ017-B	Chalcopyrite & pyrite	104	17.08	207	16.01
616-86-10	pyritized phyllite granite	794k	1.13	1064k	4.72
N210-62-4	K-feldspar granite	15M	1.05	12.4G	1.61

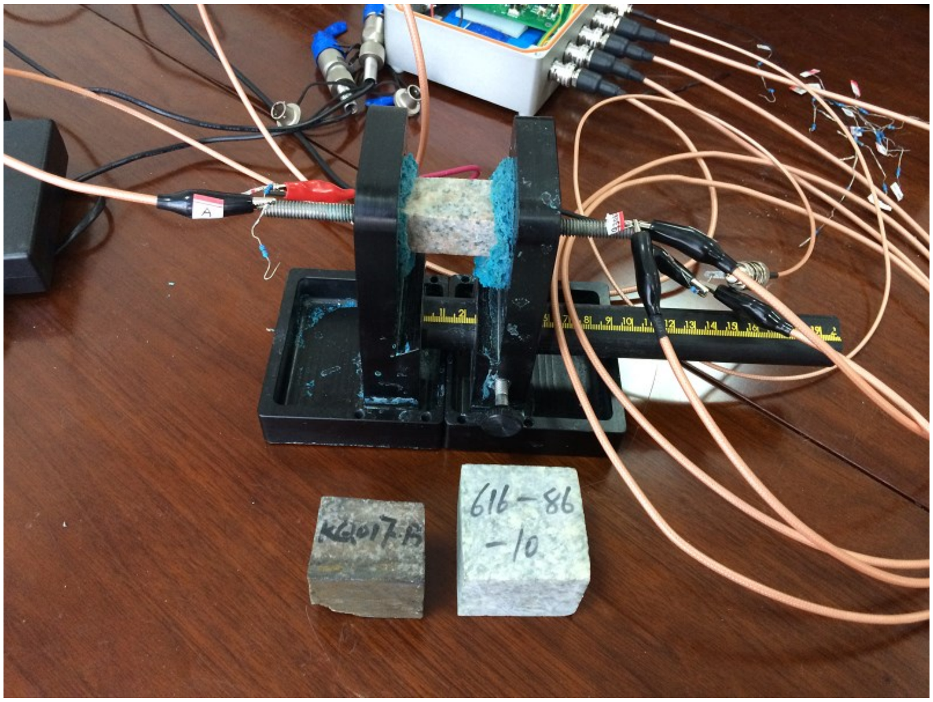

Figure 7: SIP testing for rock/ore samples

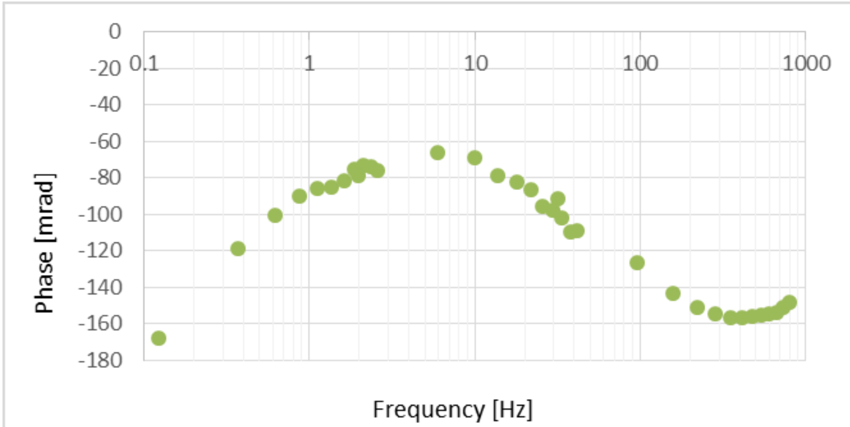

Figure 8: SIP phase response of KQ017-B

Figure 8 shows SIP phase response of KQ017-B. This result is acquired by using 3 rectangular waves and their harmonics. The discrepancy at some overlap frequencies may be caused by non-linear effect in IP phenomena, or the variation of sample holder at different time. It is necessary to control the supply current or replace the sample holder with robust non-polarized electrodes.

Conclusion and Discussion

SIP measurement for sample plays an important role in the mineral exploration, the evaluation of environment problems, the searching for clean water, and so on. This measurement process is suffered from many error sources. The situation is worse when the resistance of sample is less than 10 Ω or great than 100 kΩ. We tackled this problem by using three input buffers with state-of-art amplifiers and high precision data acquisition system which removes 1/f noise. The results of simulation and the testing results of resistors, rock samples, and ore samples show our method provides a better choice for precision SIP measurement of samples with large range of resistance. But it's still a challenging problem for high precision SIP measurement of samples with ultra-high resistance or ultra-high resistivity. It is needed to quantify errors caused by leakage current inside sample holder, and the variation of input capacitance of input amplifier related to the variation of environment temperature.

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