Electrical Impedance Tomography Technology

2013 Center Innovation Fund Final Report

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Abbreviations:

Abbreviation:	Meaning:
EIT	Electrical Impedance Tomography
EITT	Electrical Impedance Tomography Technology
DC	Direct Current
AC	Alternating Current
mA	milliAmpere (thousandth of an Ampere)
mW	milliWatt (thousandths of a Watt)
AC-CCS	Alternating Current – Constant Current Source
Hz	Hertz (cycle per second)
CAT	(X-Ray) Computed Axial Tomography
KHz	KiloHertz (one thousand Hertz)
KW	KiloWatt (one thousand Watts)
MRI	Magnetic Resonant Imaging
MHz	MegaHertz (one million Hertz)
ECG	Electrocardiogram
CIF	Center Innovation Fund
EEG	Electroencephalogram
EIDORS	Electrical Impedance and Diffuse Optical Tomography Reconstruction Software
NASA	National Aeronautics and Space Administration
FDA	Food and Drug Administration
KSC	Kennedy Space Center
BERL	Biomedical Engineering and Research Laboratory
ESD	Electrostatic Discharge
EFAL	Electronic Failure Analysis Laboratory
PCB	Printed Circuit Board
IC	Integrated Circuits
RMS	Root Mean Squared
CUDA	Compute Unified Device Architecture
GPU	Graphical Processing Unit
OTA	Operational Transconductance Amplifier
Op Amp	Operational Amplifier

Introduction to Electrical Impedance Tomography (EIT) Technology

Electrical Impedance Tomography is a relatively new imaging technology combining the techniques of electrical impedance measurements and tomography. Electrical Impedance is the relationship between a voltage applied across an object consisting of any material, solid, liquid or free space, and the resulting current. It is thought of as a measure opposition to electrical current flow with a given voltage applied. Electrical Impedance has two components - resistivity as defined by Ohms law for DC (Direct Current) voltages and reactance which is stored electromagnetic energy for alternating current or radio frequency waves. Tomography is a method of imaging by sections or sectioning, through the use of any penetrating wave [1]. In any tomography system, the location of each penetrating wave source and the receiving sensors must be known and defined in an exact ordinate system along with the object to be imaged. The receiver sensor image data is collected and fed into a tomography reconstruction software algorithm where the penetrating waves can be applied at once through the medium or can be applied one section at a time, even over a long period of time. This method of imaging is similar to X-ray Computed Axial Tomography (CAT) and Magnetic Resonant Imaging (MRI) technologies in medicine.

EIT uses a low alternating electrical current as a penetrating wave source applied through an object to be imaged, in two particular injection locations as demonstrated in figure 1. A “matrix” or multitude of voltage sensors are placed around the object to be imaged, at fixed locations, defined in a 2D or 3D ordinate systems. Voltage reading are made and recorded over the entire matrix for each time the alternating electrical current is applied. The alternating current is switched to two new injection locations and the process is repeated, all the voltages at each sensor in the matrix are measured and recorded. The process continues until the alternating current has passed completely through the object to be imaged, section by section. An EIT reconstruction algorithm, specially designed for efficient processing of the measured data set, generates an image of the interior of the object.

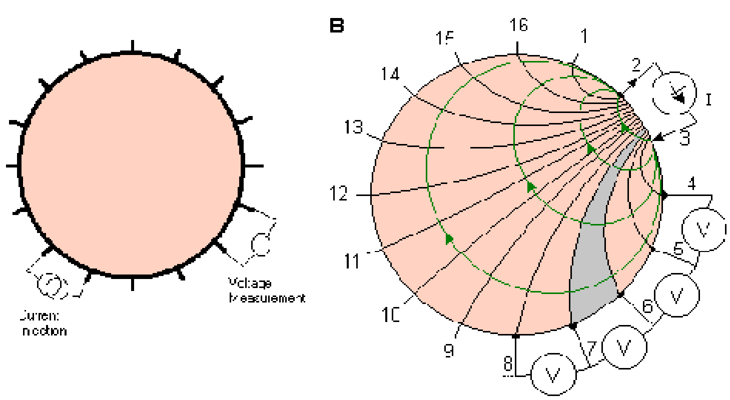

Figure 1: Alternating Current Electrical Impedance Tomography

In the medical application of EIT the imaged object is the human body itself so electrical safety must be of utmost important. EIT utilizes proven electrically safe bioimpedance measurement methods that inject alternating current signals at low precise controlled constant levels. The injected alternating is carefully limited to a very low current level of less than 2.0 mA and specified frequency level to meet international medical electrical safety standards [2]. Typical frequencies used in bioimpedance and EIT measurements range from about 3.0 KHz to 1.0 MHz. EIT electrodes are used for both voltage sensing and current application to the body and their design is typically very similar to ECG electrodes.

EIT technology does not have the high spatial resolution of a CAT and MRI medical imaging systems, but it has compelling advantages that it is a truly safe non-invasive method, that requires only simple compact and portable systems. So unlike MRI and CAT, it can be applied continually to a patient at their bedside for long term real time monitoring, using a technique that is much more comfortable and less disturbing than a CAT or MRI scan. Furthermore, it can be used easily in remote environments with results that can be telemetered to the appropriate medical source, thus not requiring on-site medical expertise to evaluate the images. Also, no imaging enhancement fluids that have medical risk need be administered, also the AC signal is low level and non-ionizing electrical energy on the order of tens of mW of power, which is safe over long periods of time; unlike CAT scan high energy ionizing X-ray radiation or the extremely high magnetic fields of MRI. In MRI a very high power RF field is evenly distributed over the body which is on the order of a KW of power, a power factor approximately 50,000 times greater than EIT. EIT technology is much safer, less risky and easier to apply for the medical technician as well as the patient and for these reasons is potentially of great utility for new medical applications and fields such as in aerospace and spaceflight.

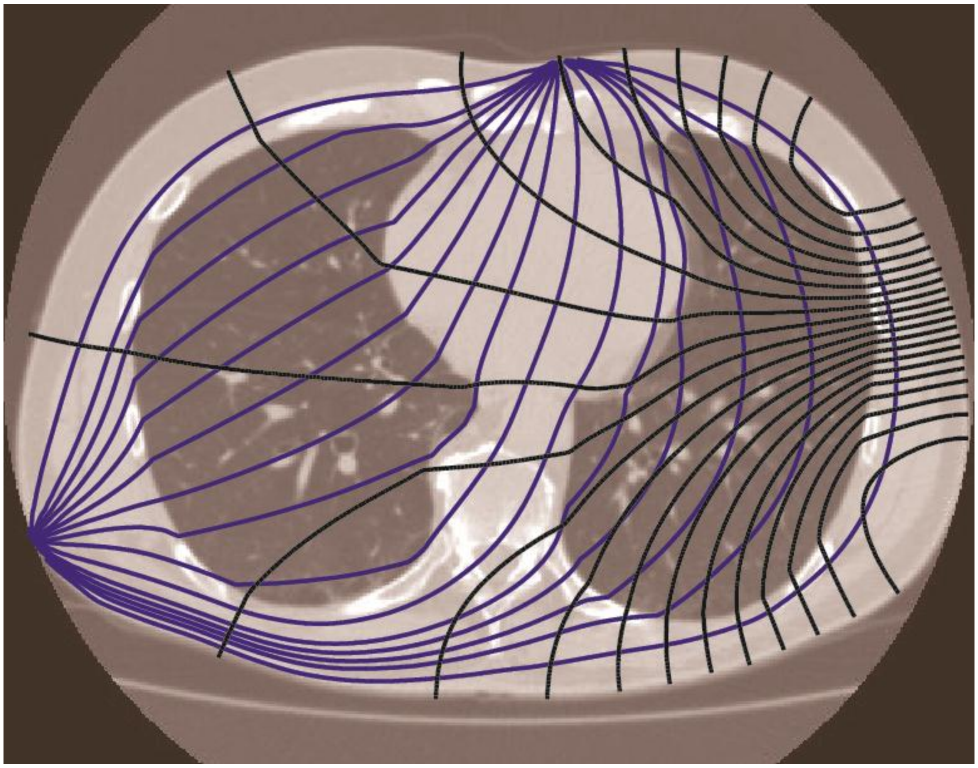

Figure 2: Illustration of current flow lines through the human thorax with different conductivities through the different multiple tissues.

The idea of using bioimpedance methods for a tomography imaging system, the basis of EIT technology, dates from 1978 and the first proof of concept system was made in a research laboratory in Sheffield England in 1984 [1]. There has been steady but slow progress in EIT technology, with medical research applications in respiratory and cardiac monitoring, the detection of breast and skin cancer and the location of epileptic areas in the brain. The primary EIT technology obstacle in the recent past has been low imaging resolution. Figure 2 illustrates the complexities of the current flow in an EIT measurement through a human thorax due to the large variation of electrical conductivities found in the human body. This complexity causes significant problems in the tomographic image reconstruction algorithm, in the form of low signal to noise ratios in parts of the electronic data set, which cause image reconstruction computation difficulties and significantly reducing image resolution. EIT computational and hardware problems and limitations held back progress in this new technology through the 1980's and 1990's.

In the past few years, advances in integrated electronics and computer technology hardware and EIT algorithm mathematics and programing techniques have moved EIT technology from the research laboratory to commercial research instruments designs for limited medical research applications such as pulmonary monitoring. Only recently have EIT systems been demonstrated with the capability to monitor real time internal motion within the human body, such as lung ventilation, with sufficient and practical resolution for clinical applications. A major contributing factor to recent advances has been the creation of an international open source EIT algorithm development group. Electrical Impedance and Diffuse Optical Tomography Reconstruction Software (EIDORS) provides an effective virtual EIT research collaboration center that has attracted new research groups that can make effective and quick use of prior work to make new contributions to state-of-the-art EIT technology. More research and development work still needs to be done on EIT technology to bring it to use and acceptance in new medical clinical and field applications.

NASA CIF EITT Project

The EITT (Electric Impedance Tomography Technology) CIF project work brings EIT Technology know-how to NASA aerospace medicine's technology asset portfolio. EIT technology is very adaptable to aerospace medicine, namely in portability, low power requirements and the ability to safety monitor patients in real time for long durations which could be critical in long term flights. Similar advantages are useful in the medical and commercial sector. An EIT system can be easily applied by first responders with minimal training, very, similar to applying a modern portable ECG system for patient monitoring. In a relatively short time, design and fabrication technologies that will improve EIT technology performance has been brought together in a first prototype design and development platform.

EIT Prototype Development:

The scope of the EIT prototype system design is bounded by the technology design challenges and the technical resources and experience available to develop the prototype in an efficient manner. The technical challenges are known; the image resolution must be improved while at the same time the time to create an image frame must be decreased for real time monitoring with an acceptable level of resolution. The challenge is dealt with by focusing on electronics hardware and firmware improvements in signal to noise ratio, faster data acquisition, and in software improvements in the EIT algorithm.

The initial phase of EIT development was to develop a set of design specifications consistent with the project goals and user requirements. The design of the EIT system was divided into subsystem design blocks, referenced by the specifications, to best allocate and focus design resources. The design subsystems blocks and components that are unique to EIT systems and critical to performance improvements were prioritized for development and testing for this first phase of the EIT prototype.

EIT Subsystem Block Diagram

The EITT system is comprised of three subsystems blocks shown in figure 3. The first component is the electrode array and lead harness block. The electrode array would be applied as a wide band or cone over a body part like the human thorax. Another possibility is a skull cap like that used in an Electroencephalograph (EEG) system for real time cranial monitoring. The Electrode array and leads harness are designed to safely deliver the EIT current signals and accurately receive the resulting body voltages at the specific electrode locations in the array.

The second block is the EITT electronics, divided into components described below, which supply and switch the test AC currents and receive and process the electrode voltages for data capture and storage. The EITT electronics perform the control and measurement functions through microcontroller operations initiated by the host computer application. The third subsystem is signal data processing and image reconstruction algorithm and display block which is the software technology section of the EIT system. The host computer must be custom built with large scale parallel processing power to support rapid algorithm imaging calculations, but it must also be reasonably compact and portable.

The EIT electronics block is divided into five design components. The first is the alternating current constant current source (AC-CCS) generator that supplies the precision constant AC signal needed to make an EIT measurement. The AC-CCS circuit is designed to convert an input constant voltage signal waveform to a fixed current output with exactly the same waveform. The AC-CCS circuit is a custom design for the EIT prototype and its performance is critical for EIT high signal to noise ratio and safety.

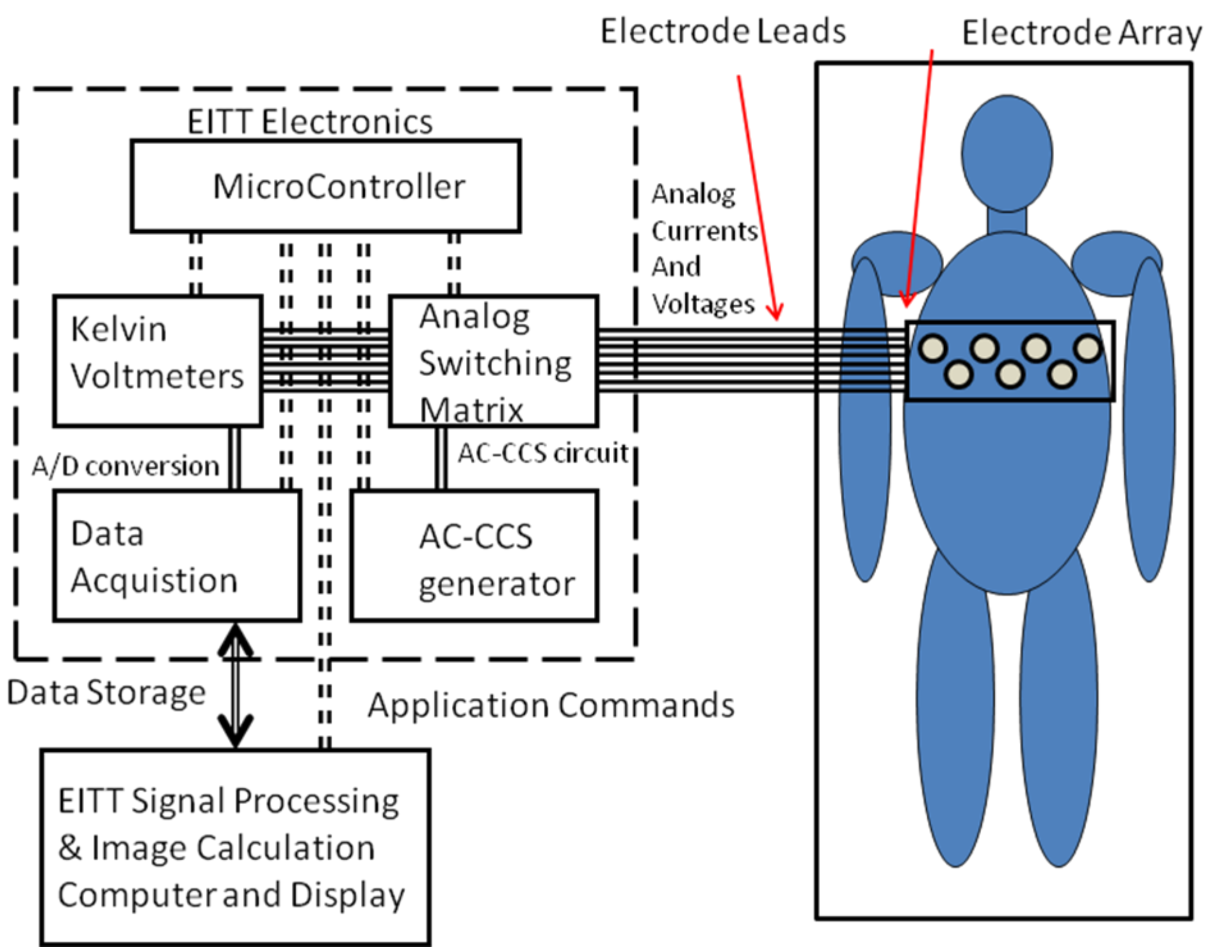

Figure 3: The EIT Component Block Diagram with Human Thorax Application

The second component is the analog electronic switching array that routes the EIT constant current signal to the specified electrode pair in the electrode array. The switching array uses commercially available electronic switching technology for low loss switching within microseconds using digital routing control and is designed to accommodate up to 32 electrodes to enhance image resolution.

The third design component precisely receives and captures the voltage at the electrodes on the body, using the bioimpedance measurement method proven for best accuracy and safety, the Kelvin four-point voltage measurement system. Sophisticated integrated electronics and instrumentation recently commercially available can meet the high performance EIT sensor hardware design requirements for EIT high signal to noise ratios.

The fourth component is the data acquisition subsystem. Its function is to record the measured voltage at the Kelvin voltmeter and accurately digitize and record the waveform in a digital file format that is compatible with EIT signal processing and image generation computer hardware and software.

The fifth component will be the microcontroller and peripheral interface circuitry which can run alone or under the control of a host computer user application. The microcontroller will directly control the EIT electronics components and data acquisition tasks and send system status to the host computer through the user application. Table 1 in specifications lists EIT prototype system microcontroller functions designed for EIT system development, practical clinical testing and clinical electrical safety

The third block is the EIT signal processing and image reconstruction algorithm block. The EIT reconstruction algorithm is used here to process the sensor data from imaging, sent and formatted by the data acquisition system. The acquisition of the initial algorithm programming code, and its development and improvement will be a collaborative process reaching out to the many EIT and bioimpedance worldwide research groups, mostly academic some commercial, allied in an new open technical forum. Effective technical collaboration is very important to bring up BERL's EIT software development capability in the most rapid and efficient manner possible. Signal processing and EIT image reconstruction calculations are made on a computer workstation that was designed for required large scale parallel processing using a new computer technology that is commercially available in a portable form factor.

EIT Design Resources Development:

EIT Hardware Prototyping Fabrication

Design and development resources availability limits the level and rate development of new technology. The Biomedical Engineering and Research Lab (BERL) has made significant progress in bringing together resources and laboratory staff experience to maximize EIT design resources, both within the Lab and with new collaboration with the Electronic Failure Analysis Laboratory (EFAL) at` Kennedy Space Center. Designing and fabricating new and custom prototype electronics for the best low signal to noise ratio performance requires superior PCB (Printed Circuit Board) technology with the smallest form factor. It is advantageous to leverage state-of-the-art integrated circuit and PCB technologies used in portable wireless devices that can deliver the best performance at low cost. In the search for a PCB prototyping system capable of the task, BERL found that EFAL had the similar need for state-of-the-art PCB circuit prototype fabrication ability for NASA failure analysis procedures, requiring duplication of any PCB system component for failure analysis. BERL and EFAL PCB prototyping technology needs are not common at NASA KSC and is one of the very few technologies not supported to such a degree by the NASA prototype shop. EFAL and BERL have pooled their resources and technical abilities developing a joint quote and purchase of an advance PCB and prototyping system, the LPKF Protolaser S, which uses a versatile precision laser milling technology that can be used on many materials for miniature precision milling[3]. Arrangements were made for staff of both BERL and EFAL for training and use of the new PCB prototyping system to cover both laboratories technical needs.

EIT Imaging Software and Computer Hardware

EIT reconstruction algorithm software technology is unique and must be acquired and mastered before operating an EIT prototyping system. The BERL joined the EIDORS software development forum and has downloaded and tested the most recent EIT reconstruction algorithm software code available [4]. EIT imaging software development requires considerable supporting computer parallel processing power to process images, which is not found in high performance desktop or laptop computers. BERL technical staff has technical experience and knowledge in new computer hardware and software technology for massively parallel processing power on desktop computers. A desktop workstation was designed and built with the new parallel processing technology, using an existing high performance desktop computer. The EIT workstation required sophisticated software modifications to the LINUX OS, which were implemented. The workstation was bench tested with a large scale electromagnetic computer analysis simulation project. With the new parallel technology the same computer simulation project was completed 26 times faster. This parallel process technology performance level benchmark is part of software specifications, and the ability to augment and speed parallel processing for rapid EIT image creation is expected to increase rapidly [5].

EIT Design Specifications:

The Electrode Array:

Electrodes should use a high reliability contact technology, such as a low hypoallergenic hydrogel for skin contact like ECG or EEG electrodes, for long term contact in a real time EIT image monitoring system and must meet all pertinent medical safety requirements.

The ultimate electrode design for EIT would also have a minimum area in order to increase the number of electrode elements in an array, while having a very reliable and comfortable contact method. The electrodes should be placed in a flexible band or other suitable geometry that would stretch evenly with different test patient sizes. The proportional distance between electrodes should be as constant as possible between patients of varying sizes, while remaining comfortable for longer term wear during real time monitoring.

The electrode leads must be very flexible as well as providing signal integrity for safe AC constant current application and accurate voltage measurements. An electrode lead array should be designed for frequencies of over 100 kHz, with a 1.0MHz goal and may include electrical shielding methods. Electrode leads should be designed to maximize patient comfort during real time monitoring.

Electrodes and leads should be constructed for easy and quick replacement as needed between testing on different patients. Electrode leads should be configured so they can be stored and quickly applied to a patient without unwanted lead tangling or twisting.

AC-CCS generator:

The AC-CCS should be driven with a programmable frequency synthesizer that can create any periodic waveform from 3.0 KHz to 1.0 MHz and provide DC offset control. The frequency synthesizer must be able to switch frequencies while maintaining constant amplitude and create waveforms containing multiple frequencies, with unwanted harmonic frequency power less than 1% for system accuracy.

The input impedance of the AC-CCS shall be high enough to isolate the input voltage waveform synthesizer or generator from any output load variation in resistance and reactance.

The AC-CCS must not operate at a current level setting equal to or greater than 2.0 mA rms under any circumstances for electrical safety.

An independent means of measuring current real time is added for electrical safety to shut down the AC-CCS if a technical malfunction were to occur causing causes the output current to exceed 2.0 mA.

The AC-CCS should also be protected or isolated from an 8.0KV human body model Electro-Static Discharge (ESD), without adversely affecting its performance.

The AC-CCS shall have internal precision fixed resistors or equivalent circuitry for self-calibration that may also serve as part of an internal current monitor system.

The AC-CCS shall work over a frequency range from a low limit of F_{min} = 3.0 KHz or less to a maximum limit of at least F_{max} =100 KHz and a design goal of 1.0MHz. The -3dB high frequency power drop should be a frequency ten times the maximum operating frequency.

The AC-CCS external load resistance variation range shall be 0 to 1000 ohms, with a current output constant within ±5%, enabling any extreme in bio-impedance measurement in the field. AC-CCS circuit design must be unconditionally stable while monitoring live patients with no instability caused by capacitive or inductive reactance effects at high frequencies or non-linear electrolyte ion flow at low frequencies.

An AC-CCS circuit should have only a minimal DC (Direct Current) content as part of its AC output, with less than 1% of the current output being DC content. This is especially important if isolation is required to remove DC offsets, high common mode voltages or provide high voltage static protection in a clinical setting.

Kelvin Voltmeter:

The Kelvin voltmeter should be of a differential configuration to measure a difference in voltage between two points while rejecting common mode voltages that may exist. The electrodes should not require direct grounding to the Kelvin voltmeter or AC-CCS electronic circuitry.

The input impedance of the voltmeter should be greater than 200 MΩ with a maximum input capacitance less than 10pF. This minimum level of input impedance is documented to be sufficient to provide for an EEG measurement system where no scalp skin abrasion is required for the patient.

The voltmeter shall have a design goal of measuring reactance, output current phase difference with respect to the AC-CCS input voltage waveform generator.

The impedance measurement, as measured on a human test subject, shall have a resistance measurement error less than ±5% and phase error less than ±10^{o}, with unconditional stability over the AC-CCS frequency range. On an electronic test load the measurement error should be less than ±1%, with a phase error less than ±2^{o}.

The voltmeter frequency response (-3dB high frequency limit) shall be approximately 10 times the maximum EITT AC-CCS operating frequency.

The voltmeter should be designed to work on floating voltages not referenced to ground, with a high common mode rejection value. It should also be protected or isolated from an 8.0KV human body model ESD (Electro-Static Discharge).

The Analog Switching Array:

The analog switch array shall withstand an up to 8.0KV human body model ESD event with electronic switches free from uncontrollable latch-up failure.

The analog switch array circuitry shall be electronically controllable from a microcontroller with a switch transition time less than 300 nanoseconds.

The analog switch on resistance shall not be greater than 30 Ω ± 3 Ω and the analog switch off isolation shall be greater than 40dB over the operational frequency band.

The analog switch array shall have a control function that will cause all analog switches to open (disable) in case of a malfunction for electrical safety.

The Microcontroller and Peripheral Circuitry Functional Requirement table:

EIT Subsystem	***Electronics Components***	***Peripheral Function***
EIT Electronics	**All components**	**Electronics System Clock & Timing**
---	**All components**	**EIT system self-check and calibration**
	EIT power supply	**Power supply controlled turn on, fault detection & shutdown**

---	**AC-CCS Circuit**	**Input Voltage Signal Generation Control**
---	**---**	**Output Constant Current Source Precision Amplitude Control**
---	**---**	**Current Sense and Over Current Fault Shutdown**
---	**Analog Switch Matrix**	**Enable: Analog Switch Routing Control**
---	**---**	**Disable - open all switches under fault condition**
---	**Kelvin Voltmeter**	**Voltmeter measurements enable and disable**
---	**Data Acquisition**	**Read new data in long term memory file, format and store**
---	**---**	**Latch and write long term data files to Host Computer**
Host Computer	**microcontroller**	**Read & Execute Host computer user application commands**
Host Computer	**microcontroller**	**Send EIT system status parameters to Host Computer**

Table 1: Microcontroller Function Requirements for the EIT System Prototype

Data Acquisition system:

The data acquisition system will have a recording digital resolution of 12 or more bits for frequencies up to 1.0MHz to accurately record the voltage waveform from all differential voltmeter in parallel in real time.

The data acquisition system will record the AC-CCS input voltage and output current waveforms to verify data at least 12 bits of resolution at 1.0 MHz.

The data acquisition system shall record and store all data in a file format that is compatible with the EIT signal processing algorithm.

The EIT signal processing software:

EITT Signal acquisition algorithm shall be run on a high performance desktop PC, which has NVIDIA Inc. or equivalent graphical processing units (GPU) with supporting Compute Unified Device Architecture (CUDA) technical standard software installed in the operating system for large scale parallel processing capability and speed, proven by software bench testing [5].

The EIT algorithm shall be developed on MATLAB (matrix lab oratory) to be compatible with the EIDORS international open forum software development group in order to participate in and take part of worldwide developments to improve the EIT algorithm and technology for better and faster image resolution [6].

The EIT display, as calculated by the EIT algorithm, shall ultimately be done in real time on a dynamic model and on human patients to demonstrate and test real time monitoring both on a computer monitor and recorded in a standard digital moving picture formant such as MPEG-4 or equivalent.

EITT Electronic Design and Test Progress

Design, development and testing of the AC-CCS circuit

In designing the AC-CCS circuit, prior peer review research work on AC constant current sources designed for bioimpedance applications and past experience was used. Four design candidates were considered and analyzed with in house electronic circuit computer simulation software. The best design, which proved to have superior performance predicted by computer analysis was selected, designed, built and tested by BREL with the design shown in figure 4.

- The *passive AC constant current source* using a high AC voltage source and a high ratio voltage divider to approximate a low voltage constant current source. This one was rejected due to impractical internal high voltages needed to make a constant current source with a 1000 ohm bioimpedance range. A design that is used today provides for a very safe bioimpedance device that is limited to a maximum bioimpedance range of 90 ohms, 10 ohms to 100, but does have the safety advantage of limiting output current on the worse case short circuit load.

- The *OTA (operational transconductance amplifier)* using the Texas Instrument OPA861. This particle amplifier design has too much current gain and does not work well in lower current ranges, below the IEC60601 maximum of 2.0 mA rms. For low bioimpedance current levels it is difficult to control using the current amplifier. The technology is worth revisiting if an OTA is designed specifically for bioimpedance applications. It has the advantage of very good high frequency response, from DC to 80MHz on both a SPICE circuit computer simulation and from actual testing experience.

- The *Howland bidirectional constant current source, basic design and enhanced design*. The Howland bidirectional constant current source is a very good Op Amp implementation of a transconductance amplifier that converts a voltage source into a current source. It has very output current control down to micro-Amps well below a milliamp, good for bioimpedance applications. It is stable over a load resistance range greater than the requirement of 1000 Ohms. On both designs the frequency response is down to DC (zero Hertz) but the high frequency limit is about only 10 KHz, on SPICE computer circuit simulations where a frequency response of at least 100 KHz is needed with a goal of 1.0 MHz for multi-frequency applications.

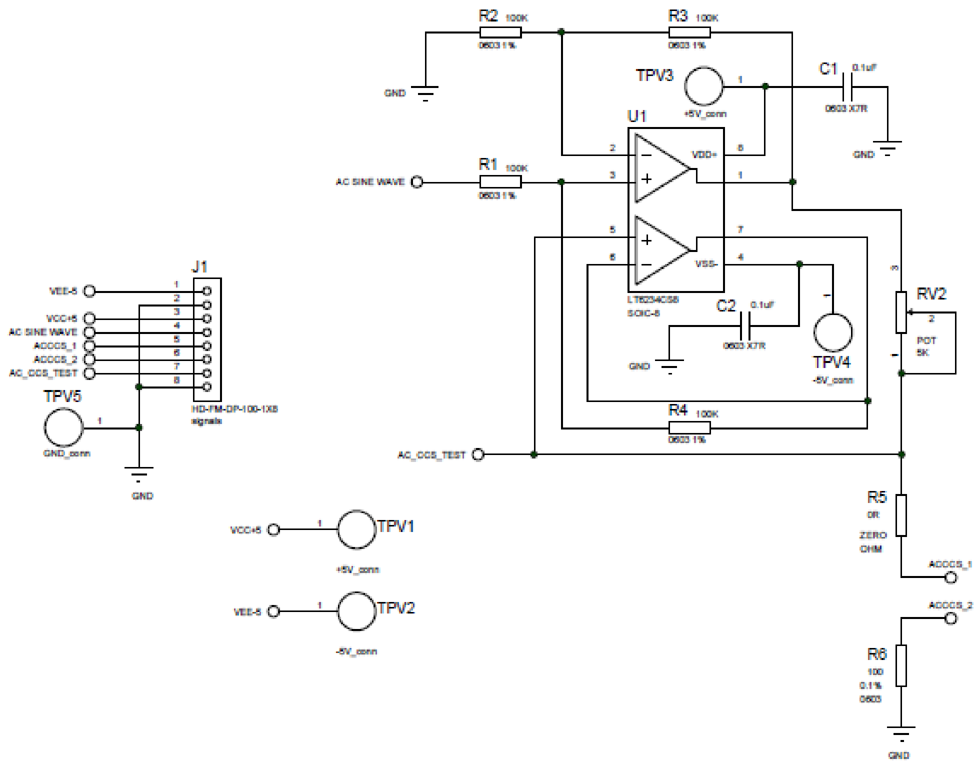

Figure 4: The schematic of the modified Howland Bidirectional constant current source implemented with the LINEAR Technology LT6234CS8 Op Amp.

- The dual Op Amp or modified Howland bidirectional constant current source (figure 4) has the good characteristics of the Howland bidirectional current control at low bioimpedance levels and has good high frequency response as found in a SPICE computer circuit simulation. This circuit was tested and the first design, which was built up, works from DC to 100 KHz making it the best choice. This circuit was found to be best in peer review journal articles [7, 8, and 9]. The load working resistance range is large also much greater than the 1000 Ohm design goal. This advantage enabled the use of an internal current limiting resistance included in the design for electrical safety and internal calibration capability

Test results of the AC-CCS using the Modified Howland design:

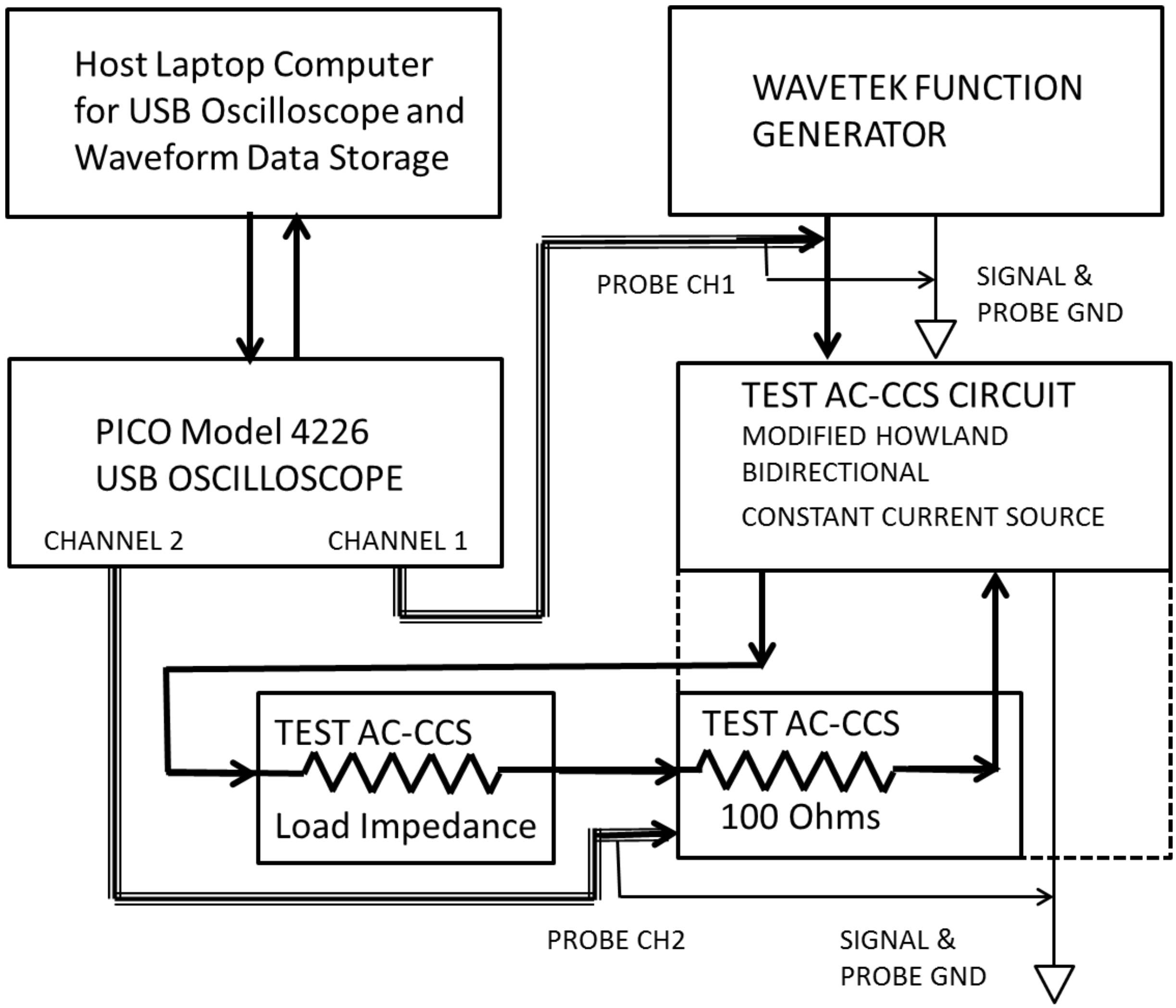

Figure 5: Block diagram of the AC-CCS circuit test measurement system

The output of the AC-CCS is across the two circuit ports labeled AC-CCS 1 and AC-CCS 2 at the bottom of figure 4 and also showing resistors locations R6. The test method diagram is shown in figure 5, where two voltage waveforms from the "WAVETEK" input voltage generator and the voltage waveform across R6 the 100 Ohm current monitor resistor are recorded and stored in digital data files. The data was analyzed and processed on the host computer. Electronic constant current sources are always limited in some degree in the range of output load where it can drive an undistorted constant current signal. AC-CCS circuit testing here explored the limits of the Modified Howland design as constructed in Figure 4. The circuit is driven above current design limits for a reliability/failure test. Since this design has no effective low frequency limit it was tested down to 10 Hertz and also tested at 500 KHz above the design limit of 100 KHz to investigate any possibility of functional failure in output current limiting.

The AC-CCS test performance indicated it could easily drive more current that designed with good control with maximum output load impedance. At lower current setting the AC-CCS can work at resistances up to 2600 ohms well beyond the design goal. In all cases within the design frequency range the current control is very good, repeatable and linear. Also in a reliability and safety test the AC-CCS limits output current safely if the output load is a short circuit or disconnected. The AC-CCS circuit design quickly responds to a new applied load with no excessive current surge if the load is replaced so accidental user electrode disconnection or electrode lead short circuits are not a problem.

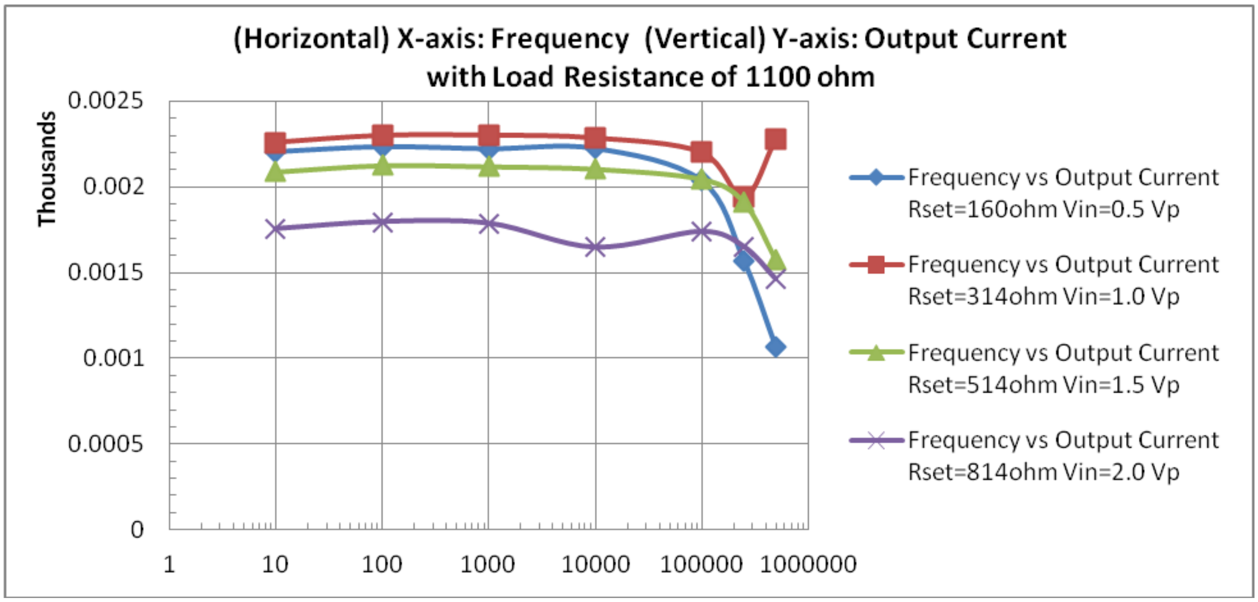

Figure 6: Output Current in units of milliamps (rms) plotted as a function of Frequency

In figure 6 the AC-CCS circuit is driven above its maximum intended current level through an outside load resistance of 1000 ohms over a frequency range of 10 to 500 KHz. The parameter on the vertical axis is the output current, which is adjusted by both the potentiometer RV1 in figure 4 and the input voltage amplitude.

Also in AC-CCS tests the current is driven to a maximum with increasing input voltage waveform amplitude. This defines the limits of operation of the AC-CCS circuit and shows ranges of best operating parameters. A 5.0 Volt power supply is works best with input signals with a maximum of ±1.5 Volts sufficient voltage where maximum design constant current can be applied to a maximum design output load of 1000 Ohms plus the additional internal current monitor resistance of 100 Ohms.

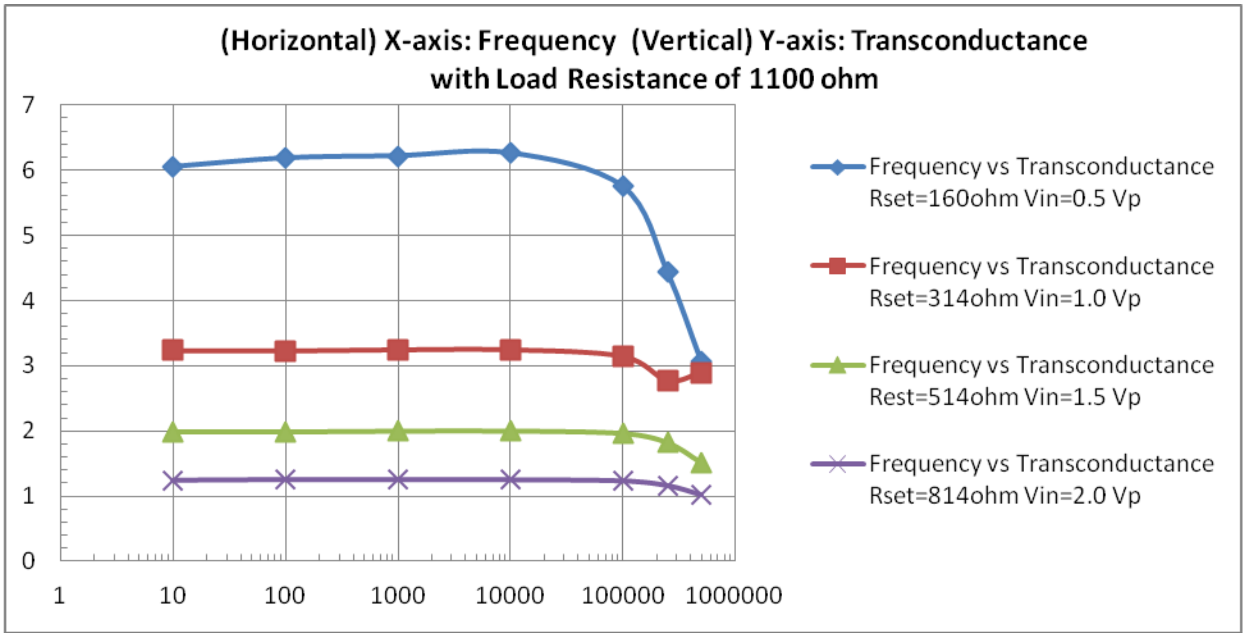

Figure 7: Transconductance in units of milliamps/Volt plotted as a function of Frequency

Figure 7 shows the AC-CCS circuit transconductance, a function derived by dividing the output current by the input voltage of the AC-CCS. Transconductance shows the AC-CCS design linearity. The constant current level can be adjusted with very good control through adjusting the control resistance Rset which is the design circuit variable resistor RV1 in figure 4. The AC-CCS response at higher transconductance values remains linear and only drops off with frequencies above the design limit of 100 KHz. Transconductance settings less than 3.0 mA/Volt are seen to be most linear.

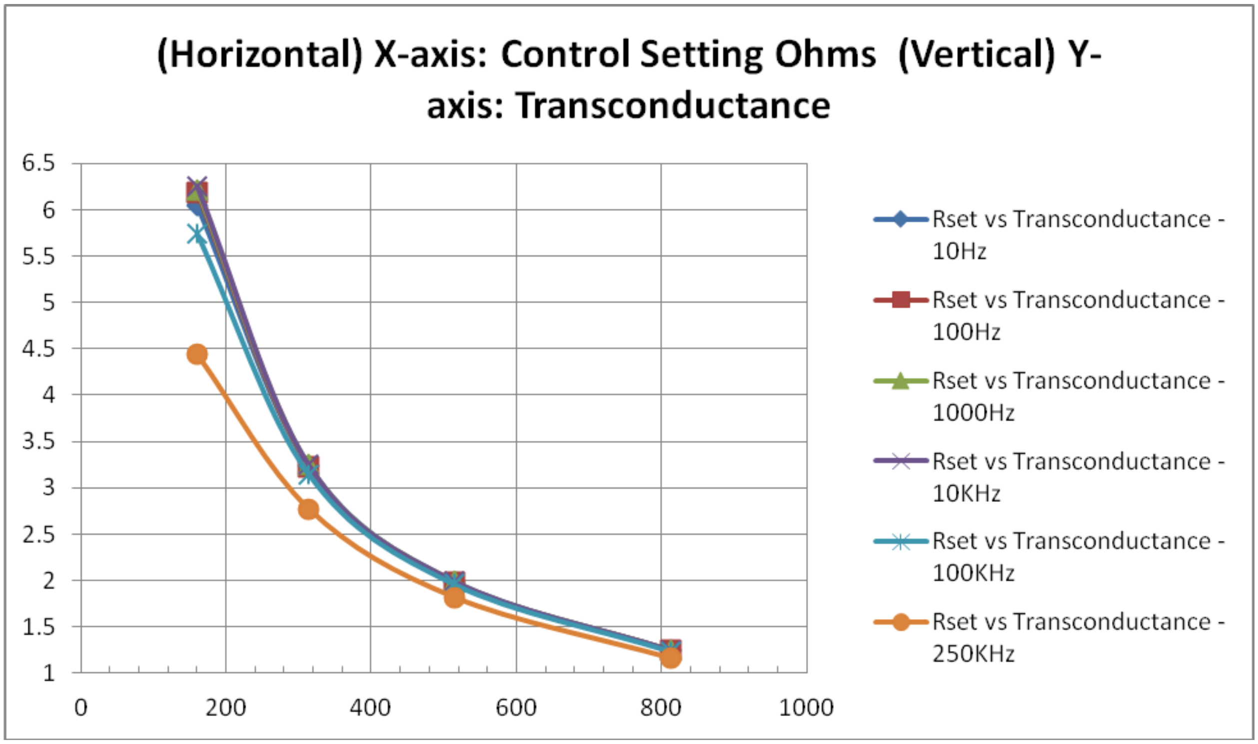

Figure 8: Transconductance in units of milliAmps/Volt as a function of current set resistance plotted for 6 frequencies

In figure 8 the AC-CCS circuit transconductance variation for variations in the set resistance of RV1 (Rset) shown in figure 4 are plotted, with 6 plots of data cover the frequencies 10,100, 1000, 10000, 100000 and 500000 Hz. Up to 100 KHz the data points coincide very closely. The transconductance versus set resistance is not a linear function, but are a smooth curve grouped close together over the design frequency band. This proves constant current level setting is invariant and remains constant over the design frequency range meaning the AC-CCS can be easily operated with multiple frequencies.

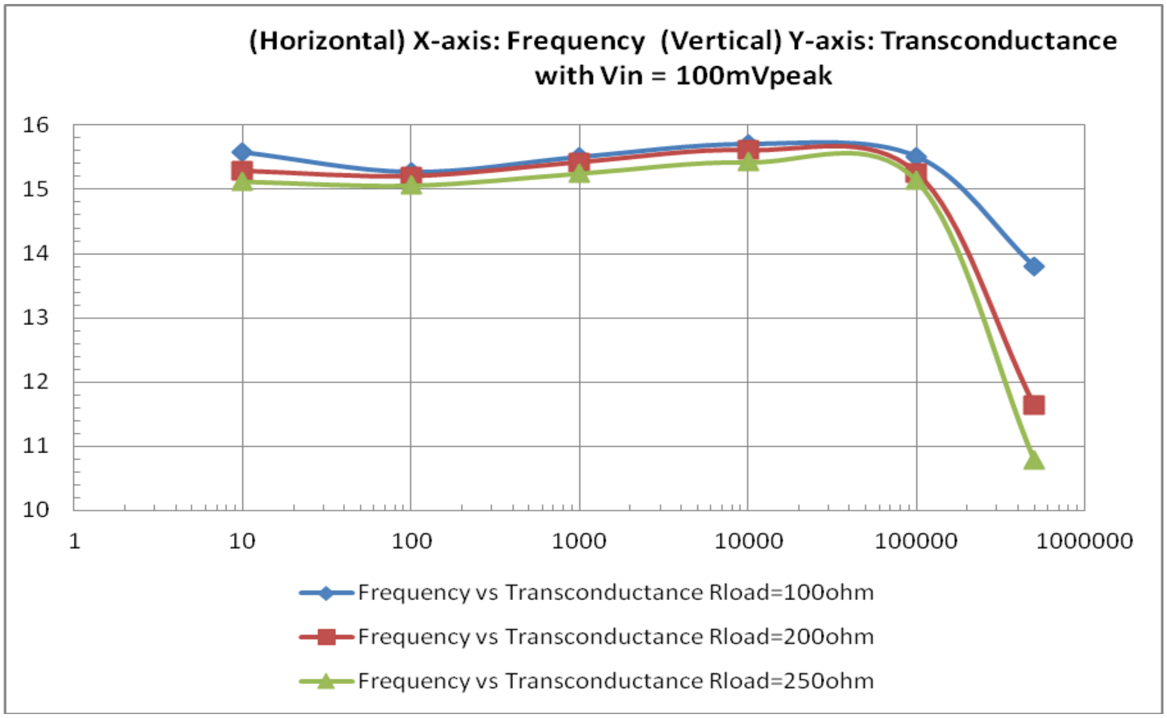

Figure 9: Transconductance in units of milliAmps/Volt as a function of Frequency, plotted for three load resistances and with Input Voltage Vin = 100m peak

AC-CCS transconductance response at lower impedance levels over the frequency range of 10Hz to 500 KHz are shown in figures 9 and 10. Figure 9 has an input voltage signal at 100 milliVolts peak. The transconductance levels are relatively high, above 15, and linear, only dropping above 100 KHz design range. In Figure 10 the input voltage signal is at 200 milliVolts peak and the transconductance levels are correspondingly lower near 6 but the transconductanc e response is even more linear.

AC-CCS transconductance vs output current settings are plotted for each frequency from 10Hz to 500 KHz in Figures 11 and 12. Figures 11 and 12 have an input voltage setting of 100mV peak respectively. The relationship between the current setting and transconductance is linear up to 100 KHz, especially with the higher input voltage and lower transconductance of figure 12 with a linear response.

Figures 7-12 show good linearity the AC-CCS circuit while adjusting circuit parameters of input voltage, current level set resistance and signal frequency, within design parameters. This is a indication of very good and simple electronic control of the AC-CCS a positive attribute.

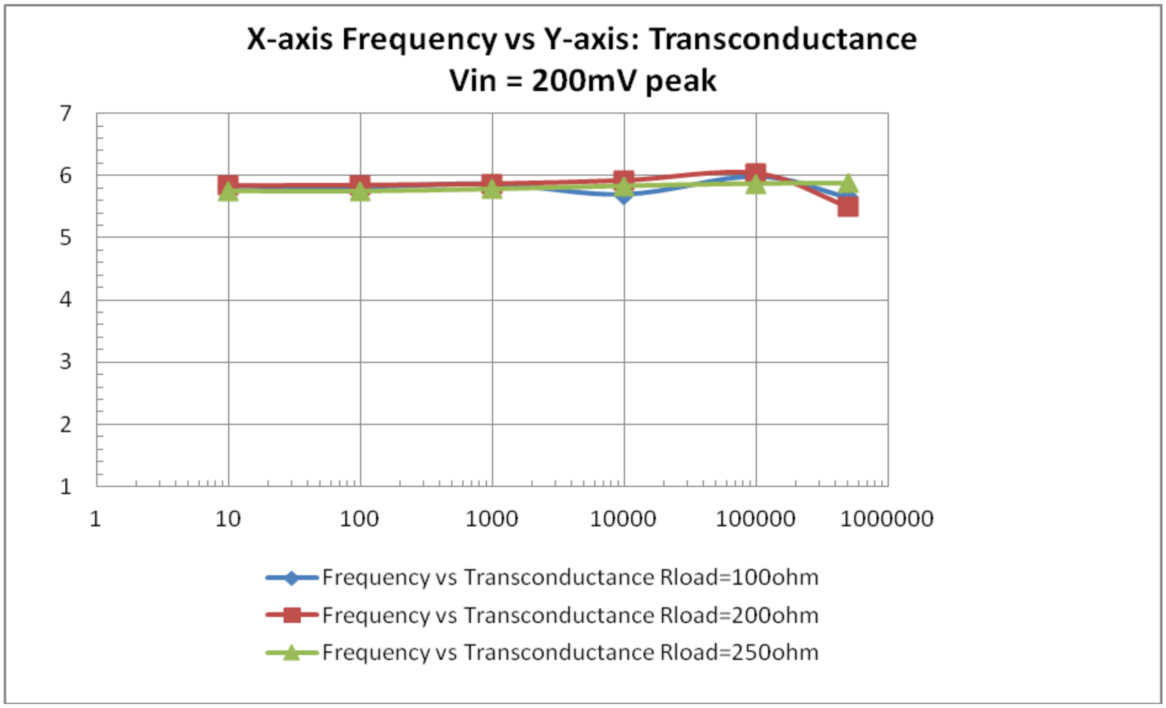

Figure 10: Transconductance in units of milliAmps/Volt as a function of Frequency, plotted for three load resistances and with Input Voltage Vin = 200mV peak

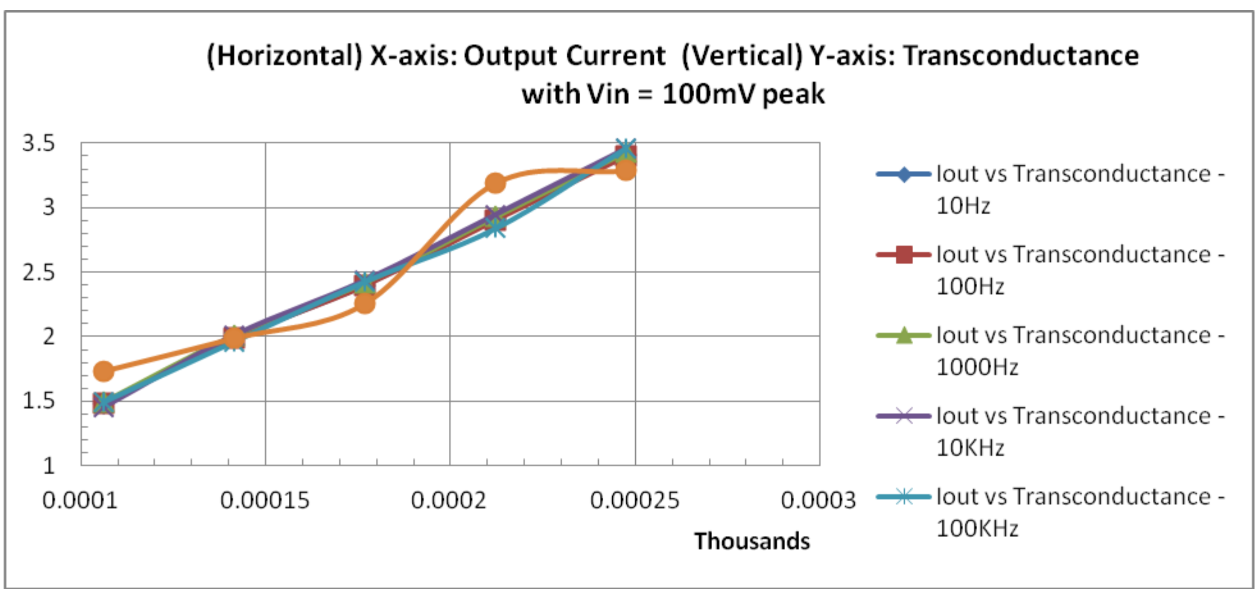

Figure 11: Transconductance in units of milliAmps/Volt as a function of output current with input voltage Vin = 100 mV peak

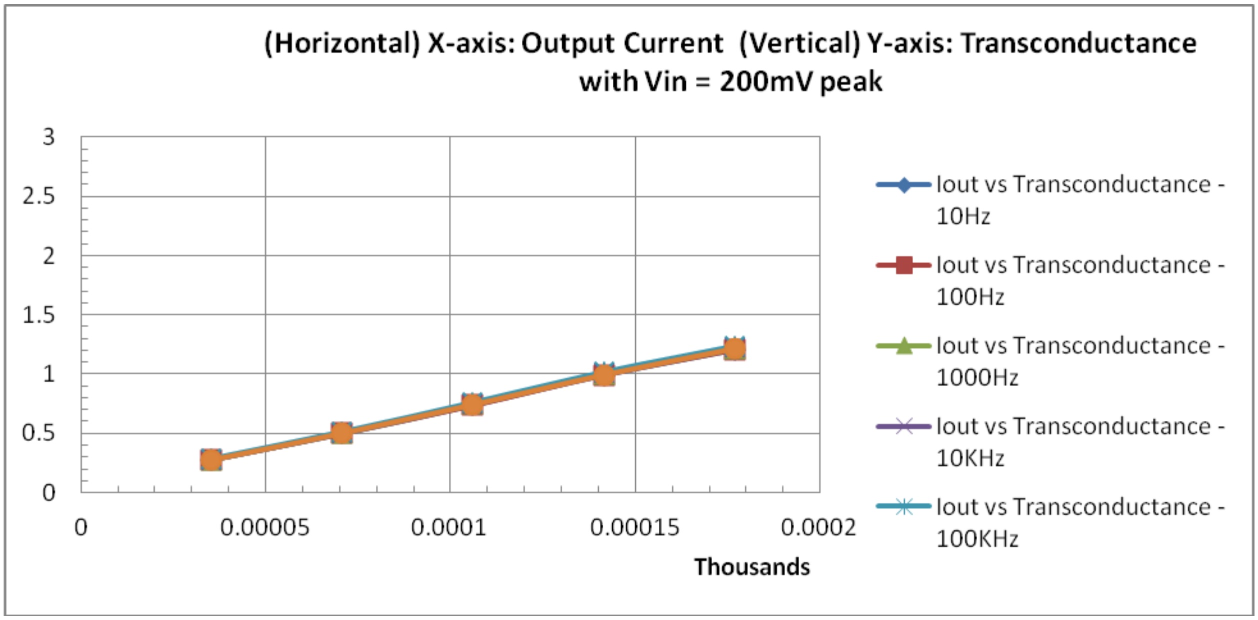

Figure 12: Transconductance in units of milliAmps/Volt as a function of output current with input voltage Vin = 200 mV peak

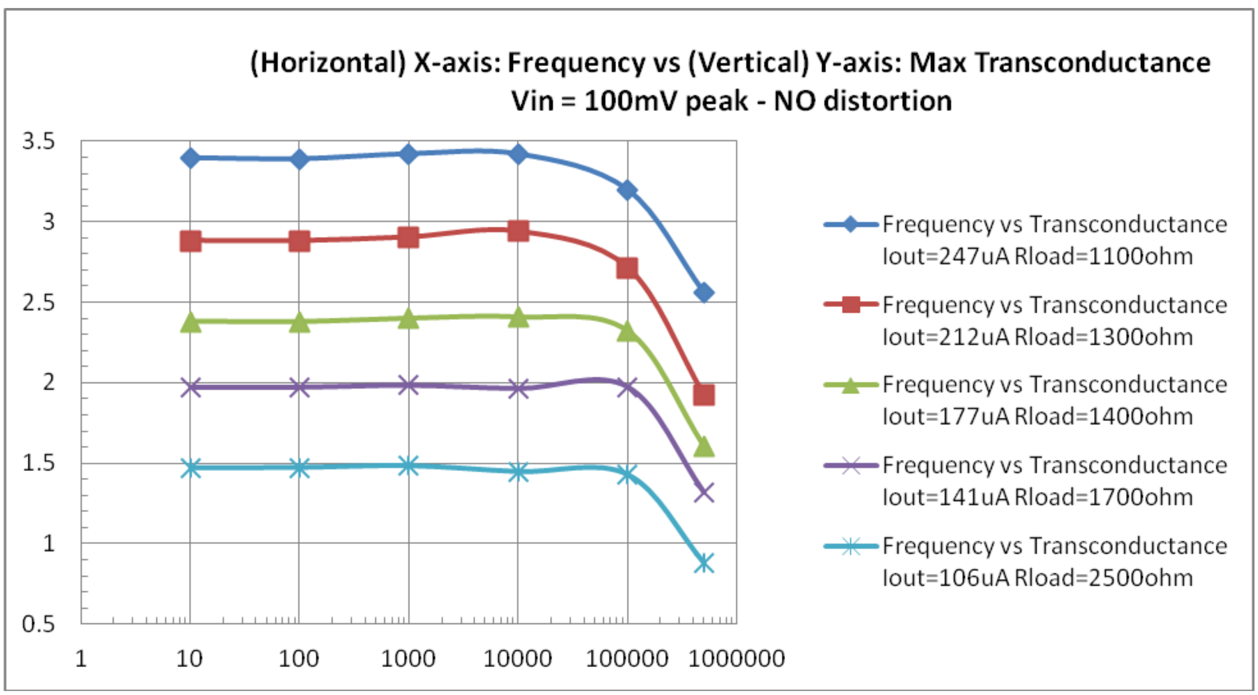

Figure 13: Maximum Transconductance in units of milliAmps/Volt as a function of Frequency, with input voltage Vin = 100mVp max undistorted current waveform observed

Figure 13 and 14 shows that the AC-CCS can supply constant current to loads much greater than 1000 Ohms up to 2500 Ohms with no output current wavefrom distortion, if the current setting is lowered. This higher load resistance capability could be useful for EEG testing especially for the willingness of test subject which is radically better if one does not have to shave the scalp and break the skin surface to lower cranial resistance.

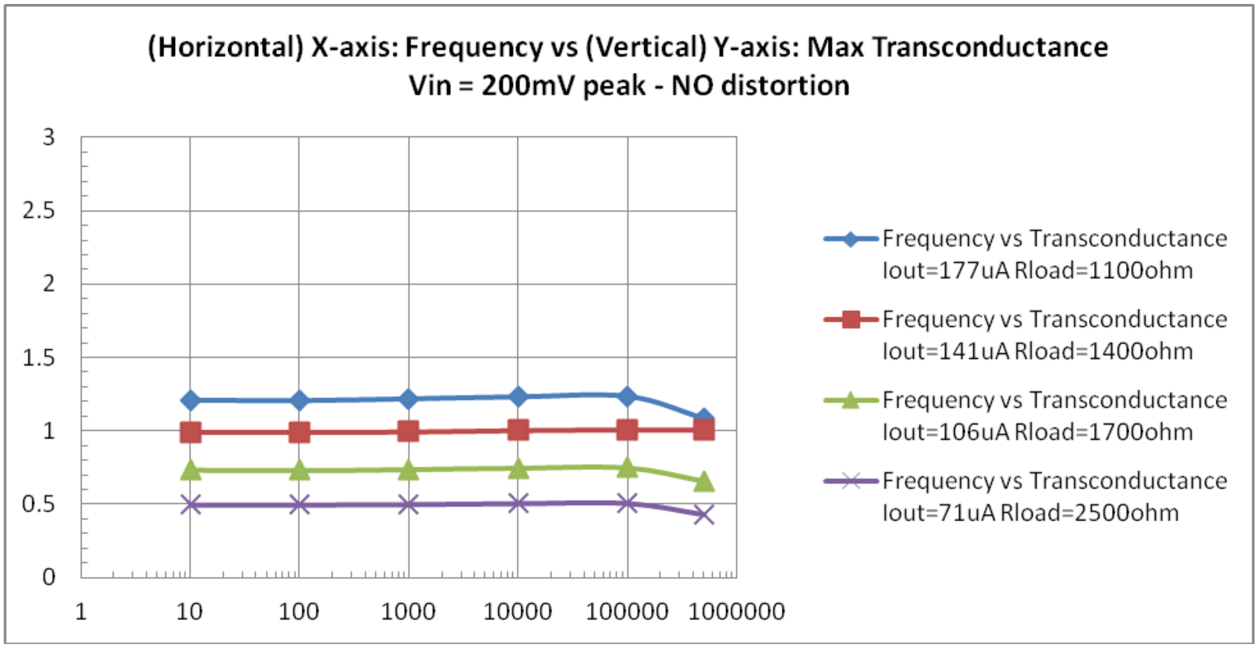

Figure 14: Maximum Transconductance in units of milliAmps/Volt as a function of Frequency, with input voltage Vin = 200mVp max undistorted current waveform observed

Summary

Electrical impedance tomography is a medical noninvasive imaging technology which has advantages over other medical imaging technogies for medically safe long term real time internal imaging monitoring applications in human patients. The technology is much more compact, portable, low power and potentially more low cost compared to other medical image technologies, making it very well suited for medical aerospace and spaceflight applications. EIT technology's main drawback has been low image resolution, and consequently improving EIT resolution is the primary research goal, as well as increasing imaging speed for real time animation imaging. In a relatively short time the BERL group has brought together design plans, technical resources and has built and tested hardware with the purpose of improving EIT imaging technology. EIT prototype system development plans and system designs have been made to target needed EIT technical improvement in electronic and computer hardware as well as EIT software technolgy. New hardware design and fabrication resources and technologies have been brought together through resourceful use of existing equipment and software at BERL, and a significant advance has been made in custom electronic hardware prototyping capabilities in collaboration with EFAL, for mutual benefit for both NASA KSC laboratories. BERL has gained significant EIT software capability and tested EIT imaging algorithm code through collaration with an internationally recognized EIT software development and research forum. A new custom workstaion has been developed, built and tested using internal resources, equipment and expertise, that includes a new state-of-the-art massively parallel technology that is commerically available. Custom prototype hardware has been designed and tested, a high priority electronic design, key to improving electronic perfromance and image quality, has been researched and tested in four designs, with a summary of test results of the selected design illustrated here. The selected design perfromance exceeds the developed EIT design hardware specifications.

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