Electrical Impedance Spectroscopy

Instrumentation Design Challenges

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Overview

- What is Electrical Impedance Spectroscopy?
- Instrumentation Requirements and Challenges
- Typical Application Areas

Electrical Impedance Spectroscopy

- Active scanning method for determining spatial distribution of electrical conductivity (σ) and/or permittivity (ε) inside a volume.
- Electrical currents applied to volume surface, generating EM field.
- Resulting surface potentials measured.
- Complex conductivity distribution may be analyzed statistically and formed into images for visual interpretation.

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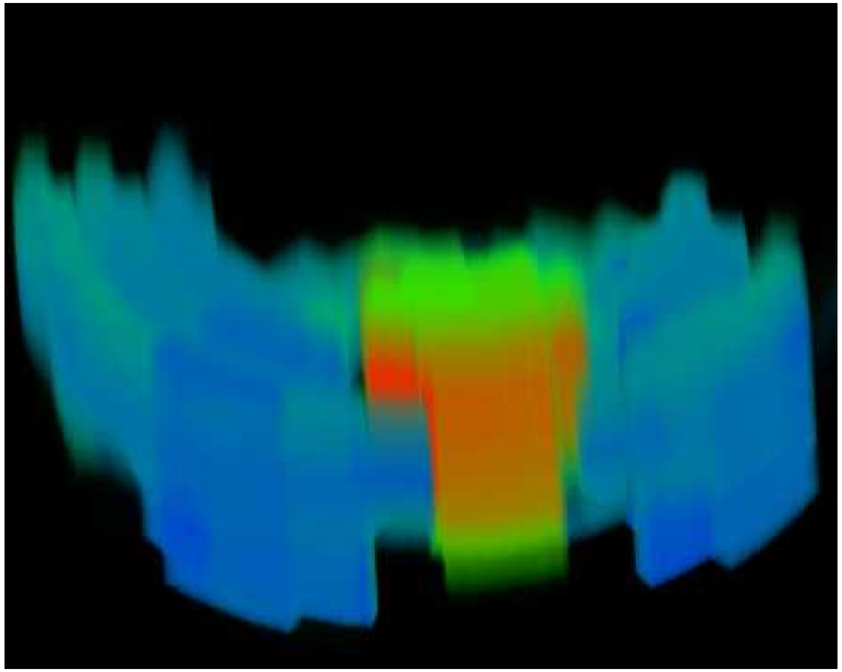
Strengths of EIS

- High temporal resolution.
- Based on electrical properties of materials (fixed and free charge carriers).
- Can characterize materials as function of intrinsic and extrinsic properties.
- Platform technology for cross-disciplinary application.

Sample 2-D EIT Imagery



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EIS Movie: Lung Ventilation

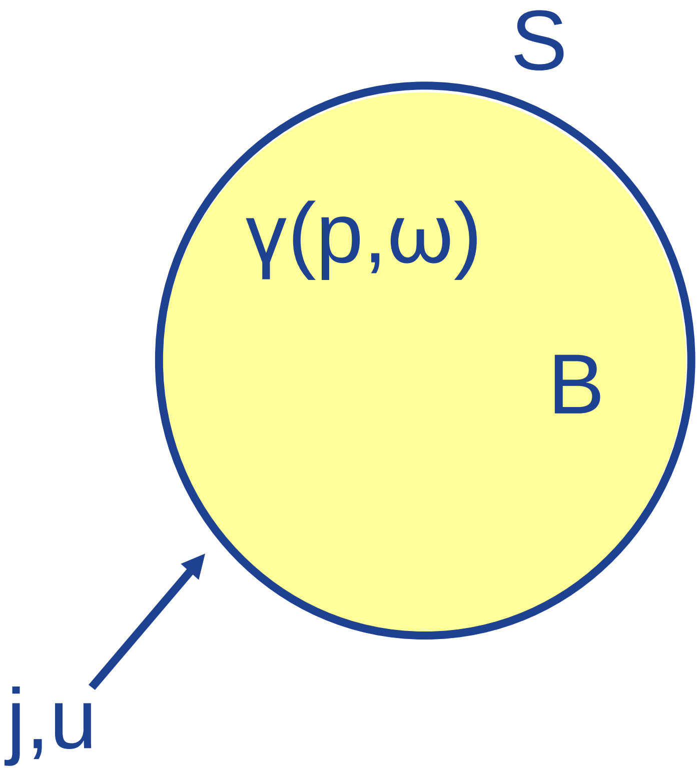
Complete EIS Forward Model

- At low frequencies magnetic field effects can be neglected.
- Assuming no interior sources, then:

$$\nabla \cdot \left[\gamma \nabla u\right] = 0 \text{ in } B$$

$$\gamma \frac{\partial u}{\partial n} = j \text{ on } \partial S,$$

$$\text{where } \gamma \equiv \sigma(p,\omega) + j\omega\varepsilon(p,\omega),\ p \in R^2.$$



Complete Forward Model (cont.)

Modeling electrodes on S:

$$\int_{e_l} \gamma \frac{\partial u}{\partial n} ds = i_l \,, l = 1,2,\ldots,L$$

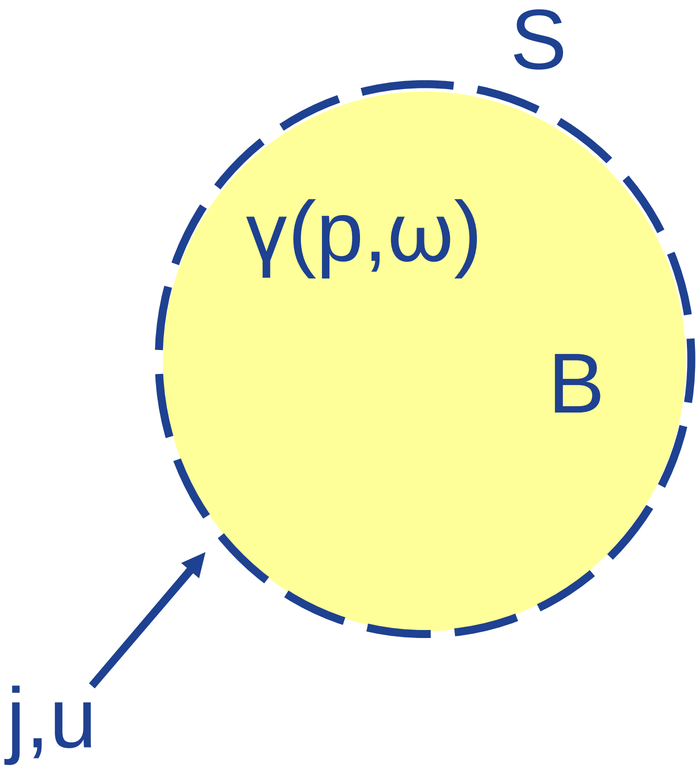
$$\gamma \frac{\partial u}{\partial n} = 0 \text{ , in gaps}$$

Modeling u on e_l :

$$V_l = u + z_c \gamma \frac{\partial u}{\partial n} \,, l = 1,2,\ldots,L$$

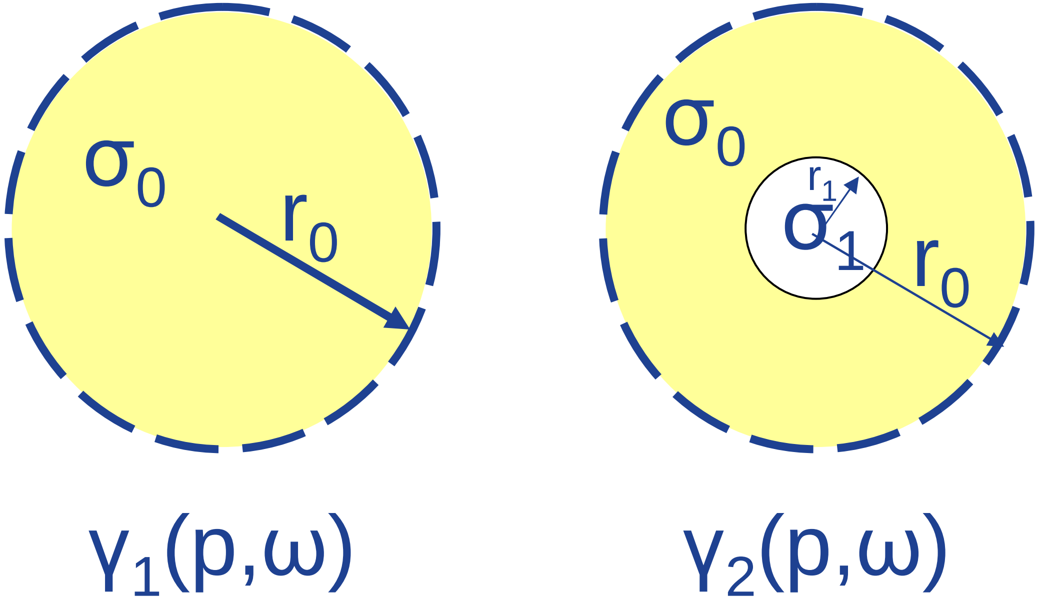
Boundary Conditions :

$$\sum_{i=1}^{L} I_l = 0 \,,\ \sum_{i=1}^{L} V_l = 0$$



Definition of Distinguishability

Ability of j to differentiate between γ_1 and γ_2



Power Distinguishability	Relative Power Change	Power Defined

$$\left|P(\gamma^1)\quad P(\gamma^2)\right| > \varepsilon_p,\quad \delta\left(\gamma^2,\gamma^1\right) = \frac{\left|P(\gamma^1)\quad P(\gamma^2)\right|}{\left|P(\gamma^1)\right|},\quad P \propto \mathrm{Re}\sum_{l=1}^{L} IV$$

Required Source Precision

Minimum source and measurement precision given by:

$$\varepsilon = \frac{\delta P}{P} \propto \frac{\delta\sigma}{\sigma_O}\frac{V_T}{V} \approx \frac{\delta\sigma}{\sigma_O}\frac{h}{H}^{3}$$

Assume:

12 x 12 cm, 64 electrode probe

Imaged depth is then ~3.59 cm

- $\mathrm{DoF}_{\mathrm{MAX}} = L(L-1)/2 = (64\times63)/2 = 2{,}016$ voxels
- Voxels have equal volume (~0.256 cm^3)
- $\sigma_O = 0.3$ S/m, with > 8:1 contrast

$$\boxed{\varepsilon_{\mathrm{required}} \geq 16 \text{ bits per source}}$$

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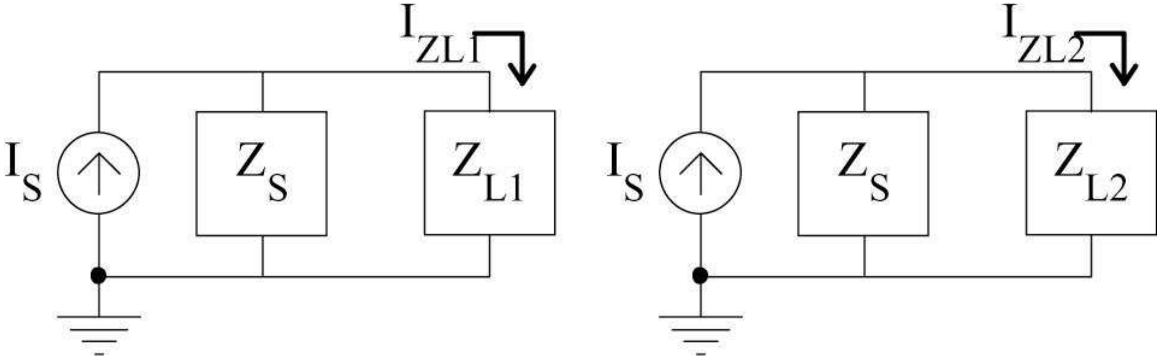
Current Source Precision



$$b\,(\text{bits Precision}) = \log_2\left(\frac{I_S}{I_{L1} - I_{L2}}\right) = \log_2\left(\frac{(Z_S + Z_{L1})(Z_S + Z_{L2})}{Z_S(Z_{L2} - Z_{L1})}\right)$$

Assume $Z_{L1} = Z_{L2} = Z_{Ln} \approx 5\ \text{k}\Omega \pm 5\%$

(Typical for electrode-skin impedance in biomedical applications)

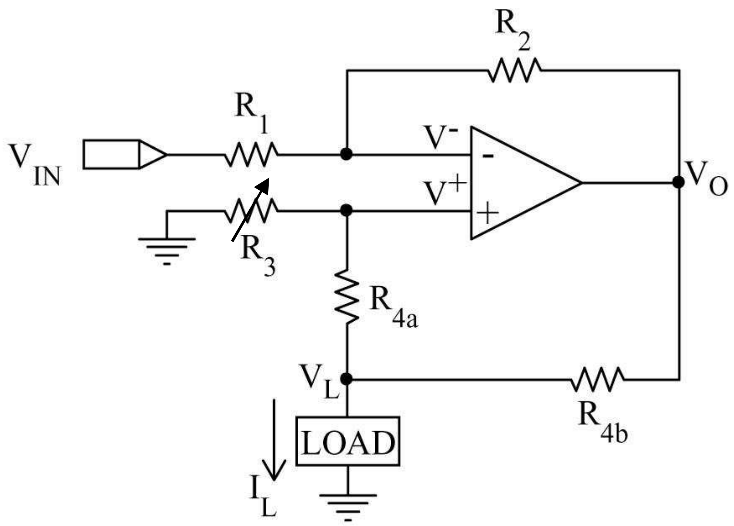
Current source precision primarily function of Z_S;

16 bit source precision requires: $|Z_S| \geq 32\ \text{M}\Omega$

Current Source Analysis: Calculation of R_{OUT} (cont.)

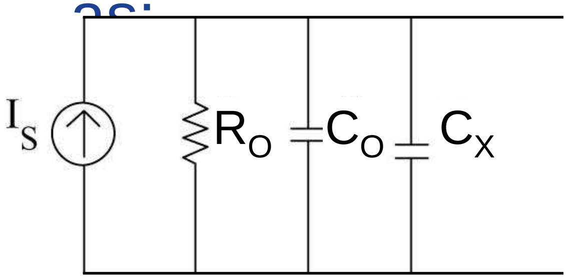
Current Source Output Resistance:

$$R_O = \frac{R_1 R_{4B}\left(R_3 + R_{4A}\right)}{R_1\left(R_{4A} + R_{4B}\right) - R_2 R_3}$$



Adjust R_3 to optimize R_O

In practice, R_O is complex, modeled as:

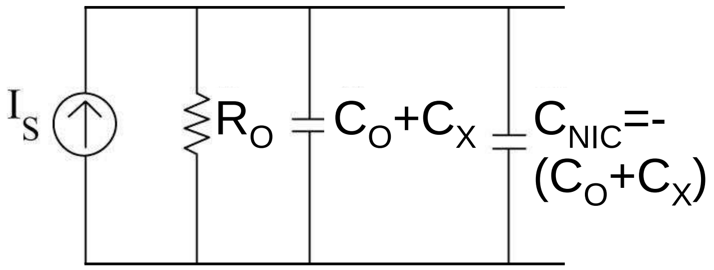


Requires compensation for output and stray capacitance.

Active Circuit Compensation for C_O and C_X

Negative Impedance Converter (Synthesizes –C)

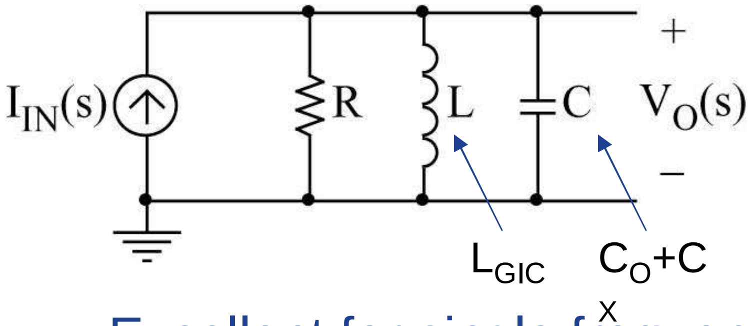
Add NIC in parallel to cancel C_O+C_X.



- Unstable at frequencies > ~100 kHz
- 1 NIC per source for all frequencies
- Simple instrumentation (single opamp, passives)

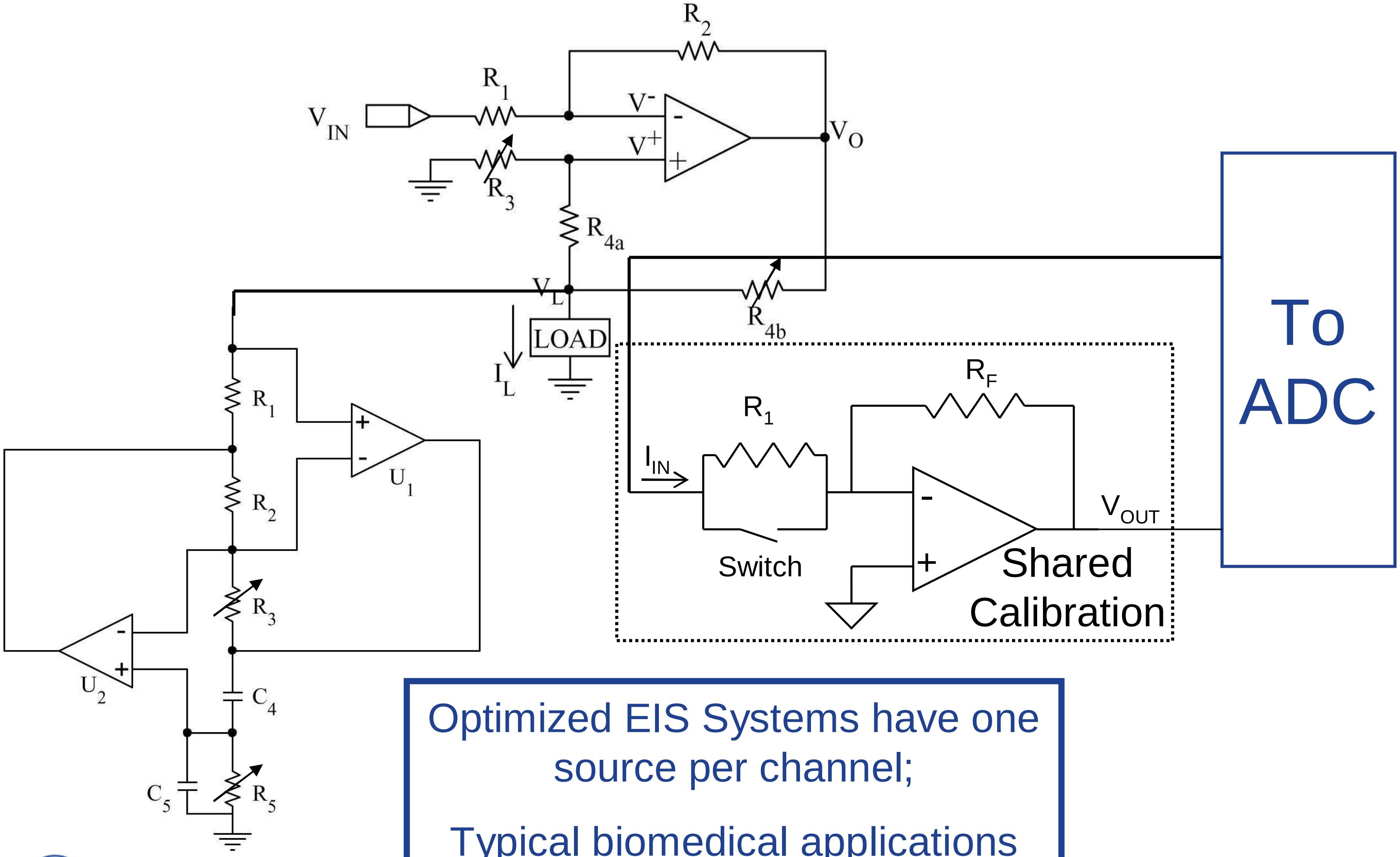
Generalized Impedance Converter (Synthesizes L)

Add GIC in parallel to achieve resonance.



- Excellent for single frequency applications up to ~10 MHz
- 1 GIC needed per source, per excitation frequency
- Complex instrumentation (two opamps, digipots, passives)

Single Channel Circuitry (Simplified)



Optimized EIS Systems have one source per channel;

Typical biomedical applications call for 32 – 64 channels.

Typical Instrumentation

- Current Sources
- Voltmeters
- Data Conversion Subsystem (i.e., DACs, ADCs)
- Safety Subsystem
- Calibration Subsystem
- Communications and Control Subsystems
- Power System and Distribution

Development Drivers

State of the Art (2008)

- 19” x 20” x 48” form factor
- Draws 1 kW
- 20 frames per second
- 72 channels

Market Requirements

✗Small form factor (e.g., laptop)

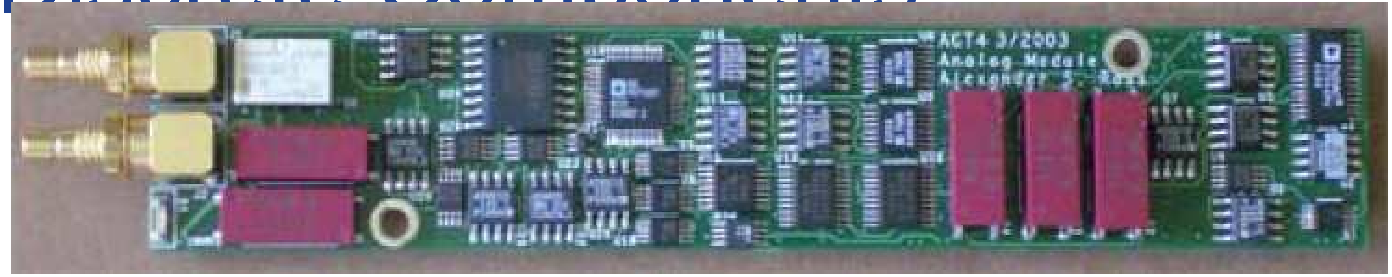
✗Low power (battery option)

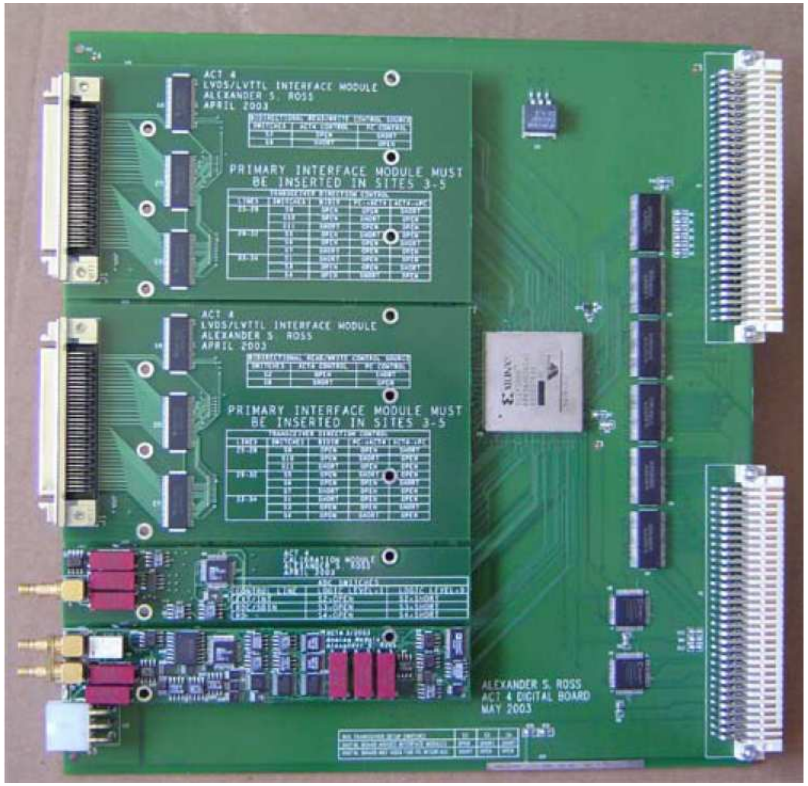
✓≥ 20 frames per second for realtime imaging

✓64 Channels for higher spatial resolution

Requires compact, integrated, low power electronics.

Completed Multilayer PCBs with Sources:
All Discrete Components





Application Areas

Biomedical

- Detection of internal bleeding
- Neurological Imaging
- Epileptic Source Localization
- Cancer Detection
- Pulmonary Perfusion and Ventilation
- Gastric Emptying
- Cardiac Events

Inspection Technologies

- Flaw Detection
- Material Characterization
- Multiphase Flow Metering

Industrial Processing

- Mixture Homogeneity
- Temperature Distribution

Environmental Monitoring

- Pollution Monitoring
- Groundwater Tracking
- Salinity Estimation

Thank You!

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