High Temperature Instrumentation

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An outline of the talk…..

- Who we are

- Resistive Johnson Noise Thermometry

- Inductive Johnson Noise Thermometry

The ***Monolithic Systems Development Group*** Spans A Broad Spectrum of Application Areas

- Experimental Physics Detector Systems
- Bio-Science Instrumentation
- Distributed Sensor Systems
- Harsh Environment Electronics
- National Security
- Molecular Electronics/NanoScience
- Novel Instrumentation Systems

ORNL Has Developed High Temperature Sensor Systems (Sensor, Materials, Packaging, Electronics)

- Vehicle exhaust gas flowmeter (650^{0}C, 100 to 1 range, fast response, low DP)
- Two-phase flow & liquid film thickness probes (800^{0}C, severe thermal shock)
- Non-contact phosphor thermometry has been demonstrated for turbine, steel processing, and automotive diagnostics over the past 10 years for temperatures -100^{0}C to 1700^0 C
- Multilayer ceramic sensors demonstrated to 1000^{0}C for O_2
- Coupled MEMS with micro-optics spectrometer (Integration of miniature black body source and off-chip detector
  - Micro-scale Midwave IR sampling cell on a chip – Concept viable to >500^{0}C
- Nanotriodes for high temperature amplification

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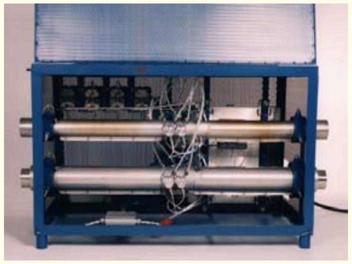
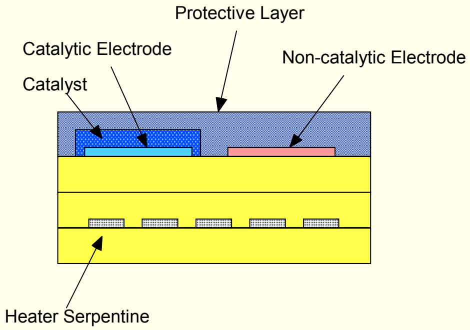
Vehicle Exhaust Flow

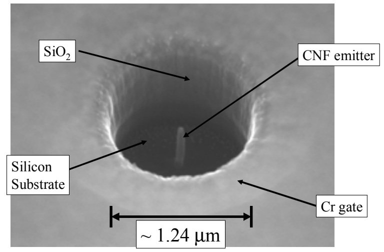


Liquid film probe

Phosphor thermometry

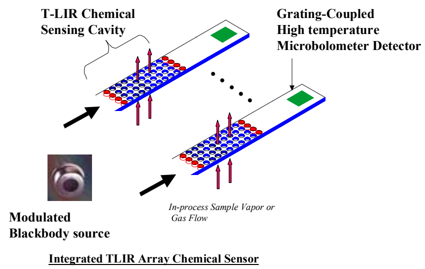
Ceramic Gas Sensors





Nanotriode

Micro Spectrometer



Temperature Measurement Needs Are Never Met for Long

- Metals industry needs non-contact temperature measurement
- Industrial diamond and ceramics industries need very high temperature measurement (>2400°C)

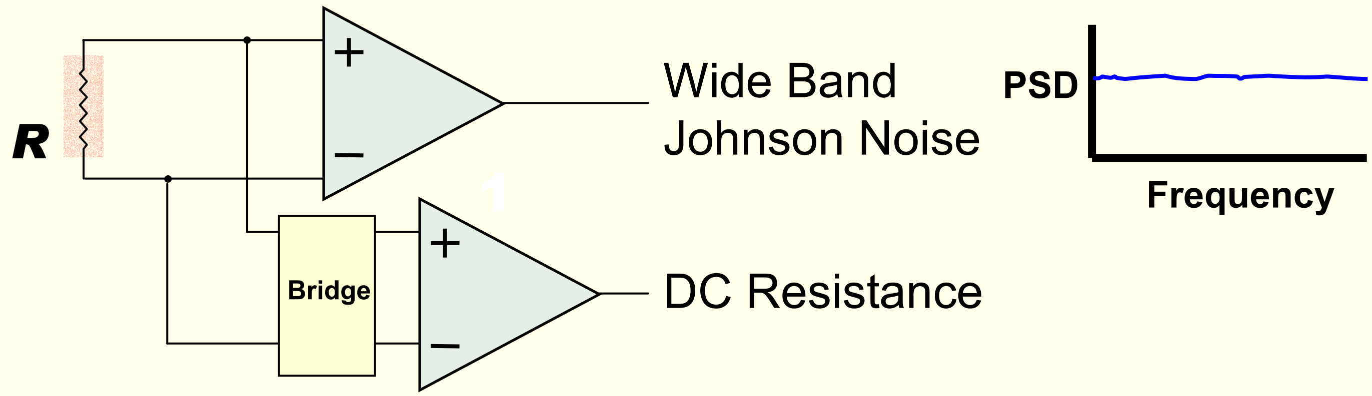

What Is Johnson Noise
Thermometry?

It's Well Known That Thermal Noise Generates Electrical Signals

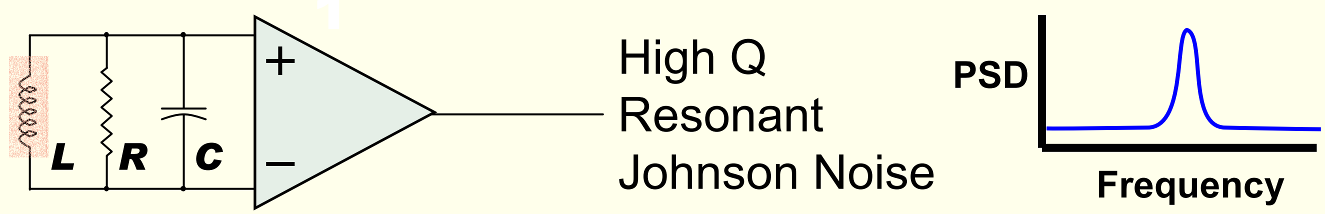
- Johnson noise is caused by random thermal motions of electrons in a conductor. This motion causes an open-circuit voltage across any resistance, which is random with zero mean. The relationship between temperature, resistance, and voltage generated is given by the Nyquist relation
- $\langle V^2 \rangle = 4 * k * T * R * \Delta f$ (Nyquist relation)
- JNT has been under development over 30 years
  – Applied in nuclear power applications
  – Mean-square noise voltage can be inductively or directly measured

Johnson Noise Can be Measured Conductively or Inductively

- Conductive Johnson Noise



- Inductive Johnson Noise

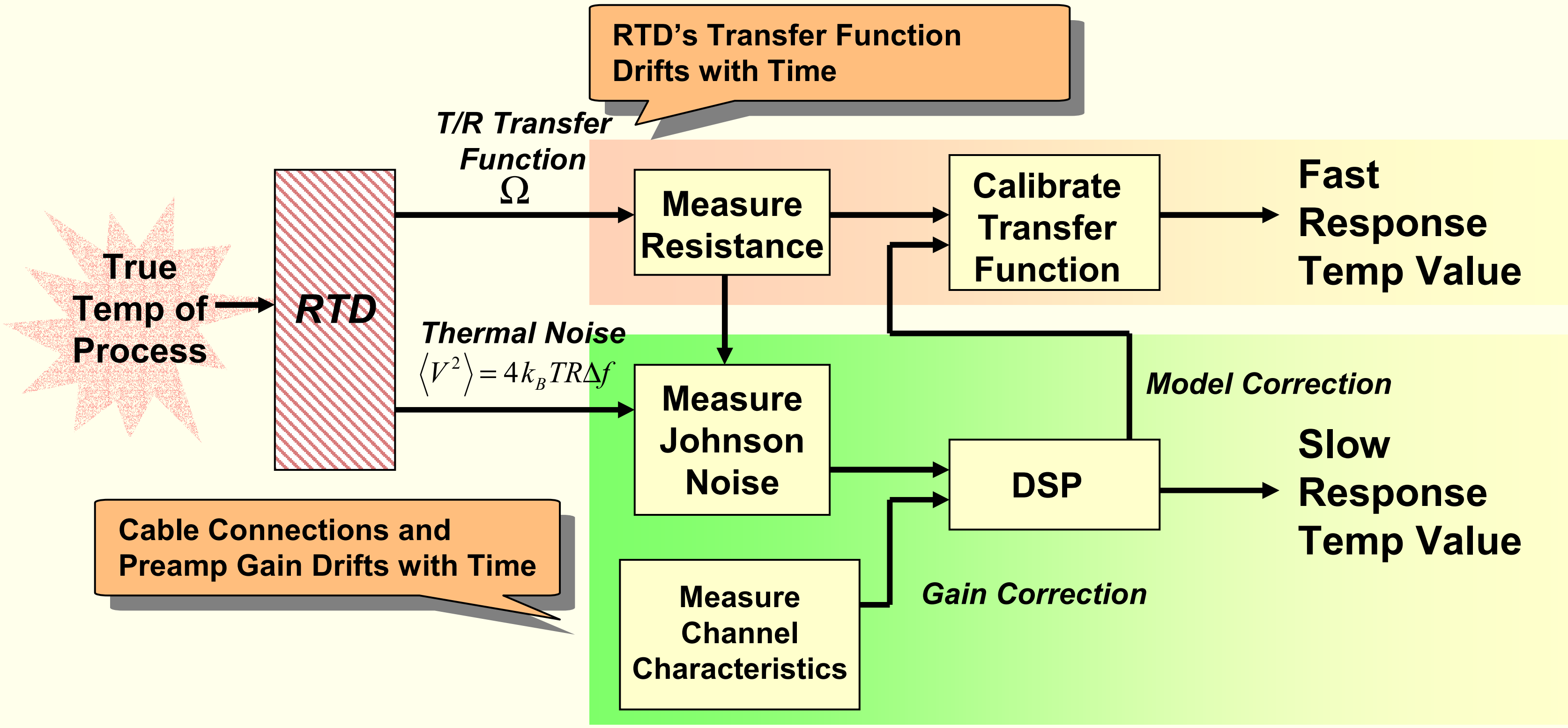


We Are Building on the Pioneering Work of Others

- ORNL major developer of noise thermometry (contact only)
  - R. L. Shepard, T. V. Blalock, M. J. Roberts, "Dual-Mode Self-Validating Resistance/Johnson Noise Thermometer System," ORNL patent 5228780, issued July 20, 1993
  - Problems with EMI, microphonics, complicated, contact only
- Preliminary INT was built and tested by Finnish researchers
  - T. Varpula and H. Seppae, Inductive Noise Thermometer: Practical Realization," Rev. Sci. Instrum. 64 (6), June 1993, pp. 1593.
  - H. Seppae and Varpula, "Inductive Noise Thermometer: Theoretical Aspects," J. Appl. Phys. 74 (2), July 15, 1993, pp. 771
  - Problems with EMI and antenna noise (could not apply to aluminum)

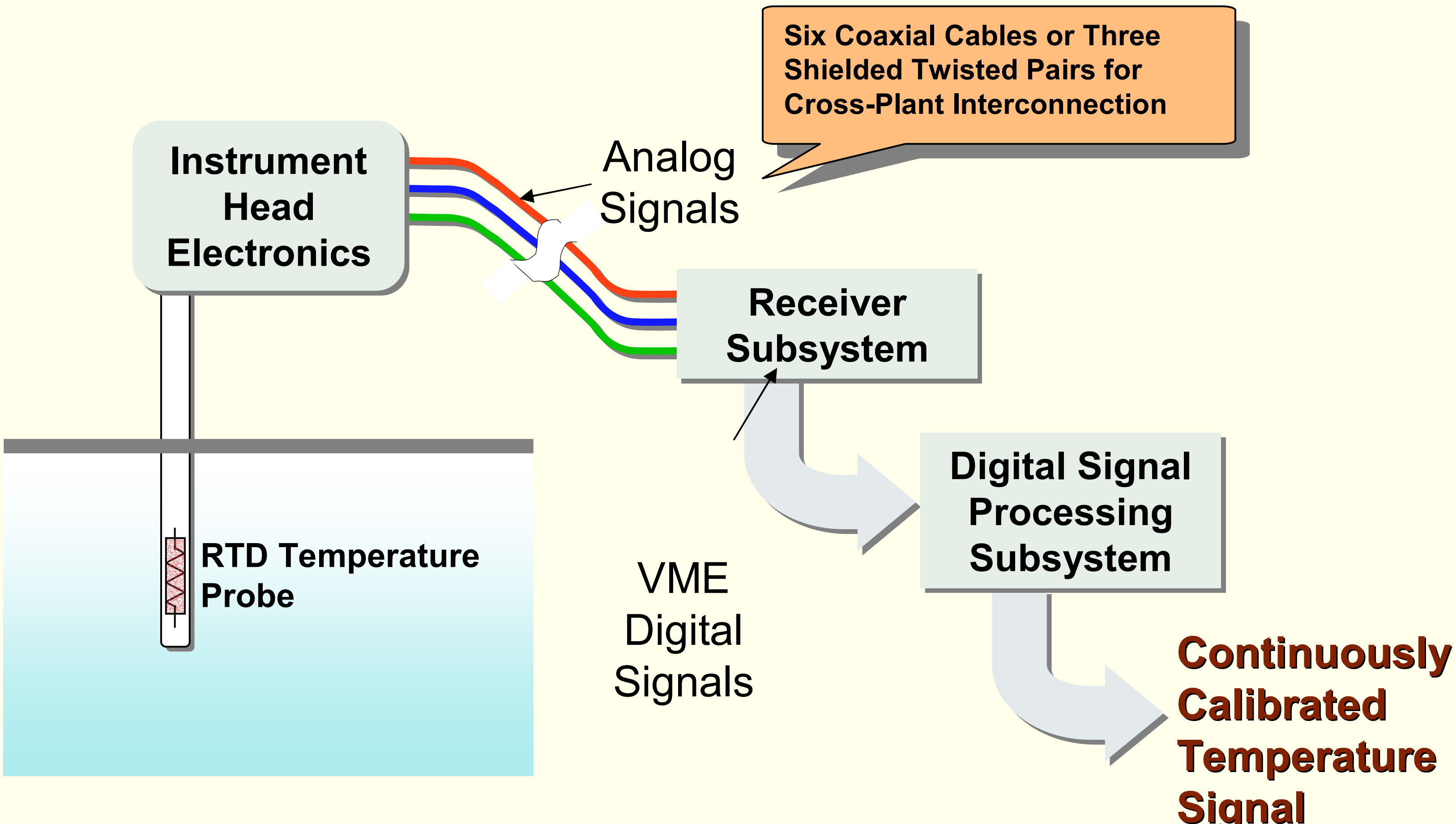
Conductive Johnson Noise Thermometry

A JNT Functional System

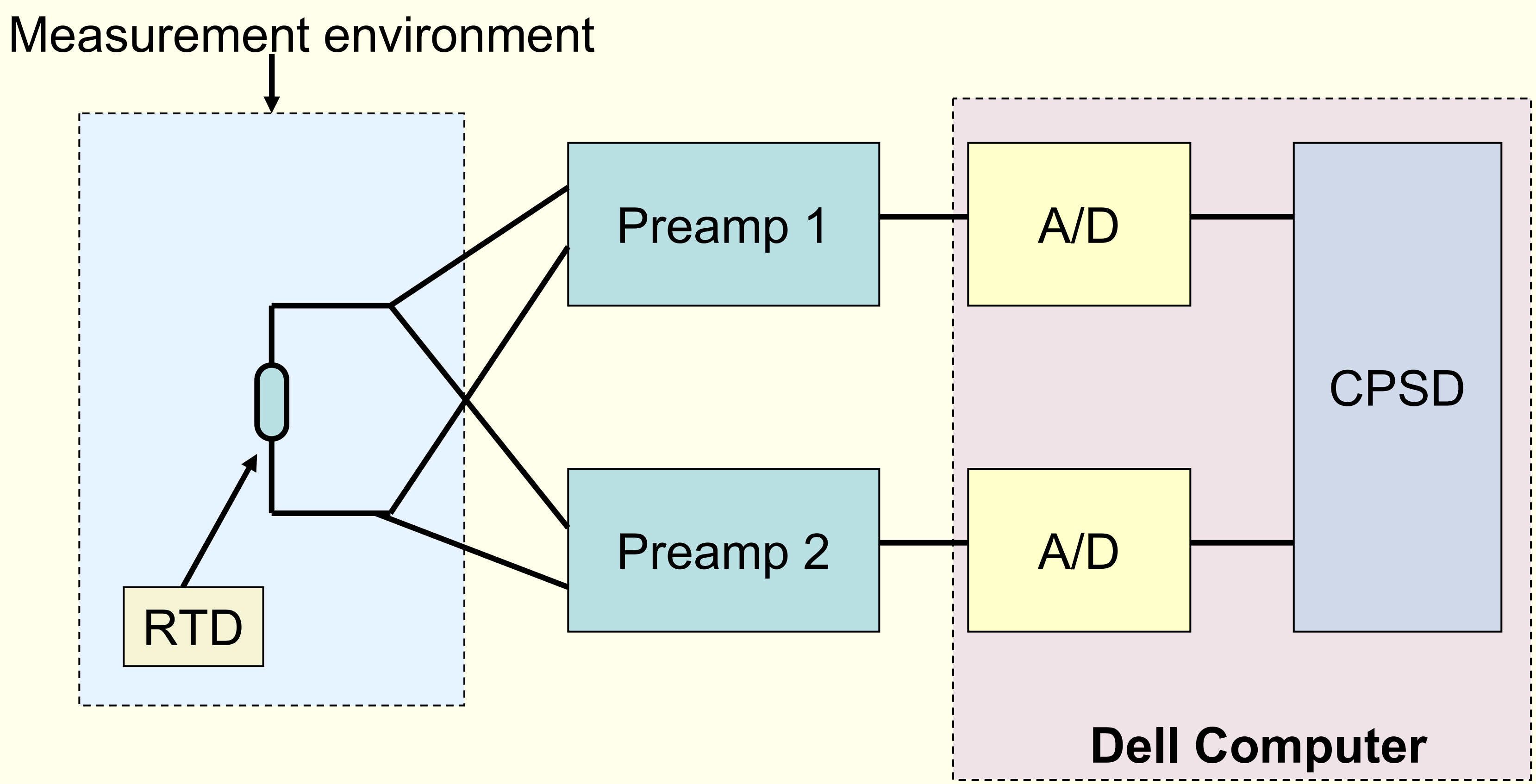


- **Accurate temperature value is obtained by Johnson noise: Requires long term integration. RTD resistance must be accurately measured.**
- **Transfer function produces fast response but subject to drift**
- **Periodically calibrate R/T transfer function with JNT**

Basic Johnson Noise System Components for Nuclear Power Plant



Signal Flow Path in Apparatus



Johnson Noise Temperature

Measurement Instrument for Reactor Coolant Leg

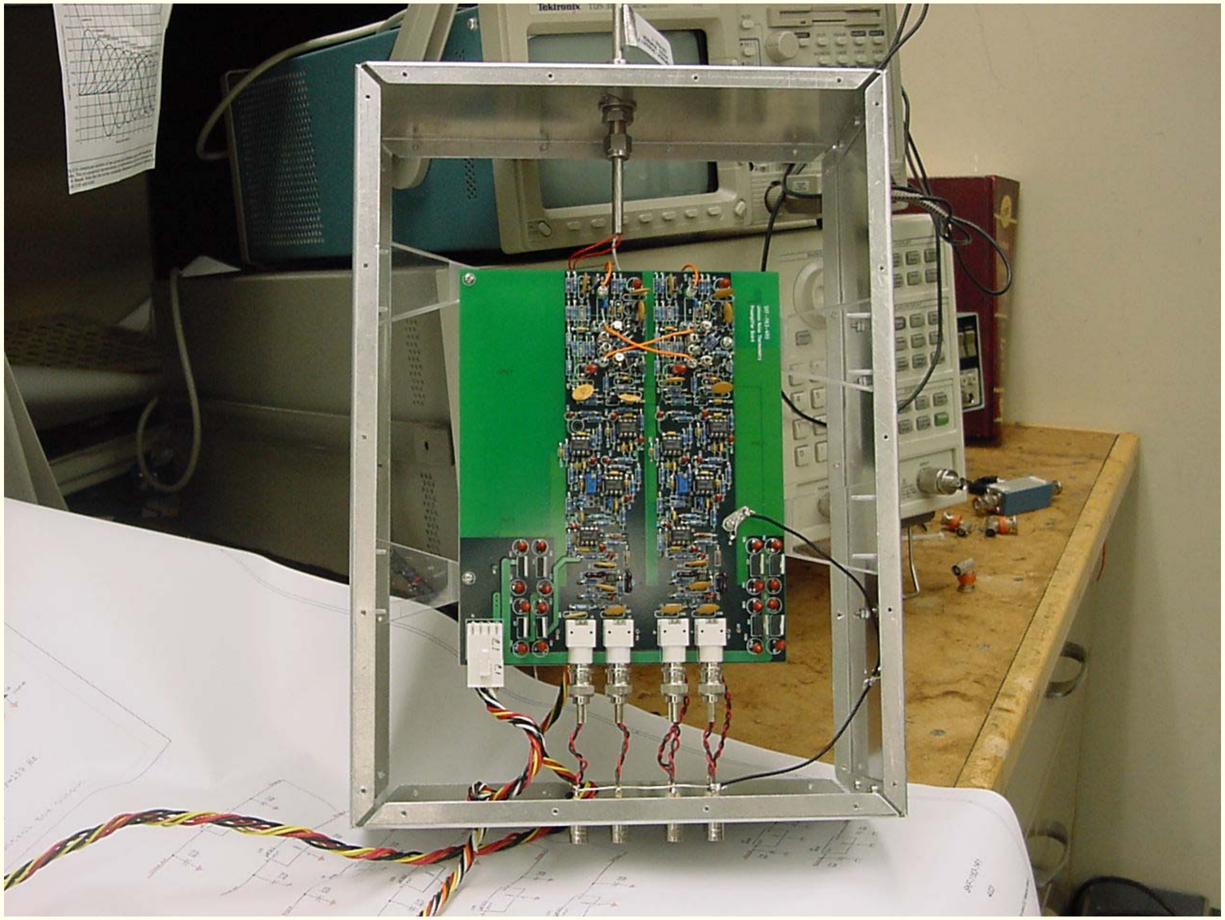
Target Specifications

- Temperature Measurement Range
  - 25 °C to 450 °C (limited by resistive material)
- Uncertainty
  - 0.2% of reading (improves with integration time)
- Power Requirements
  - Instrument head powered through local power supplies
- Calibration
  - Completely self calibrating through Johnson noise reference
- Environmental Conditions
  - Instrument head ambient to 40 °C (limited by semiconductors)

Two Temperature Measurement Methods Are Combined to Give One Accurate Value

Measurement Method	Positive Attribute	Negative Attribute
Resistance	• Fast Response • Industry standard	• Drift • Need to calibrate
Wideband Noise (Johnson)	• Fundamental temperature measurement • Needs no calibration	• Noise signal must be processed and integrated • Slow response

Dual High-Frequency Preamp Channels and DC Measurement



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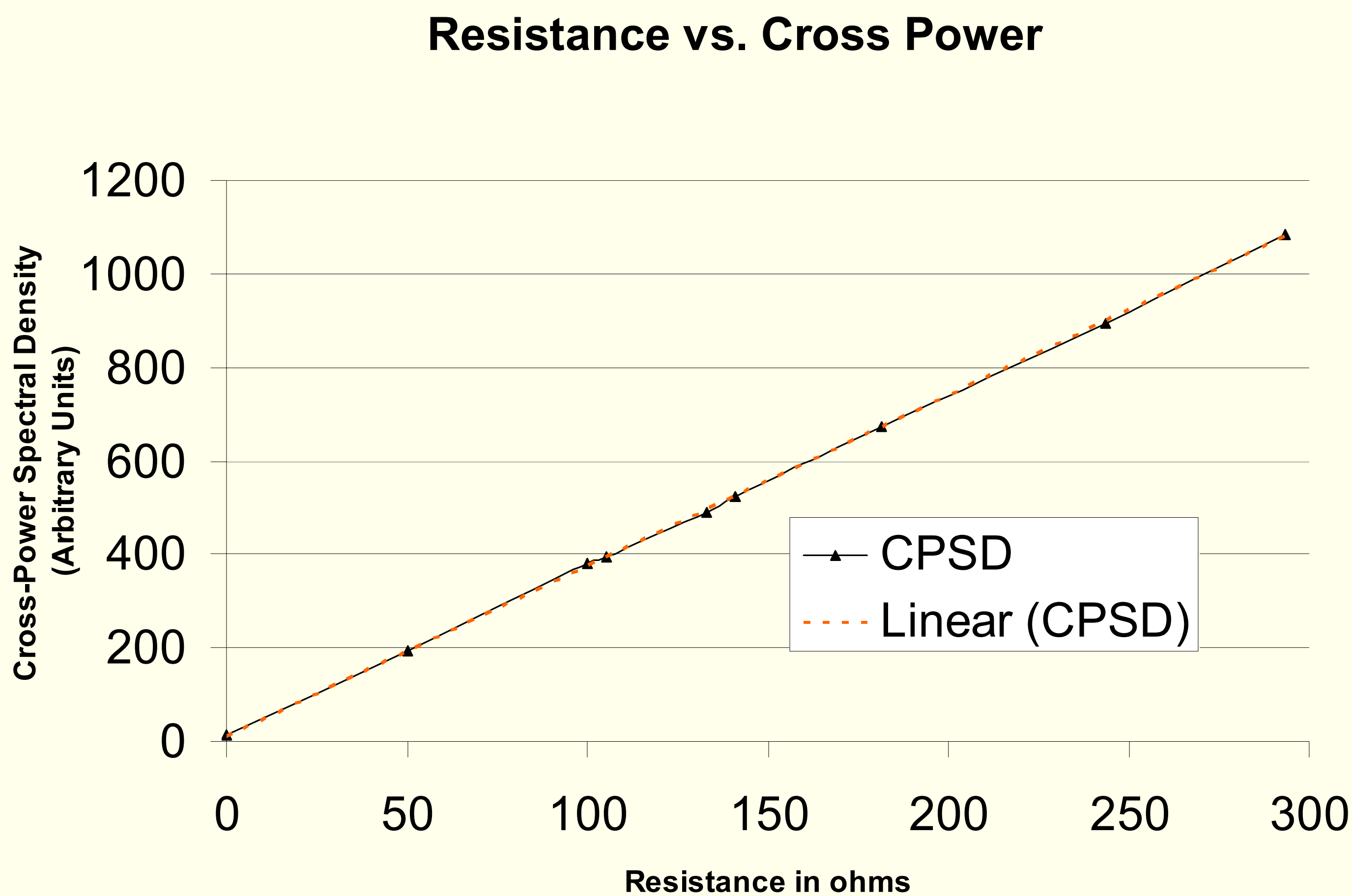
Cross-Power Removes the Effects of the Common Electronics Paths



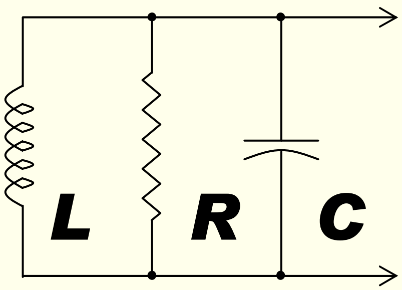

Inductive Johnson Noise
Thermometry

Comparison of Non-Contact Thermometry Methods to Inductive Noise Thermometry (INT)

Technology	Disadvantages relative to INT
Eddy Current	Depends on material properties
Fluorescence	Deposit fluorescent medium
Acoustic	Depends on material properties
IR Pyrometry	Affected by emissivity, surface conditions, and intervening atmosphere

Resonant Johnson Noise No Longer Depends on Resistance Values

- **Resistance of the metal provides thermally dependent noise**
- **All losses *R* from mutually coupled circuits become paralleled (noise adds)**
- **Voltage fluctuations are independent of *R* and *L***

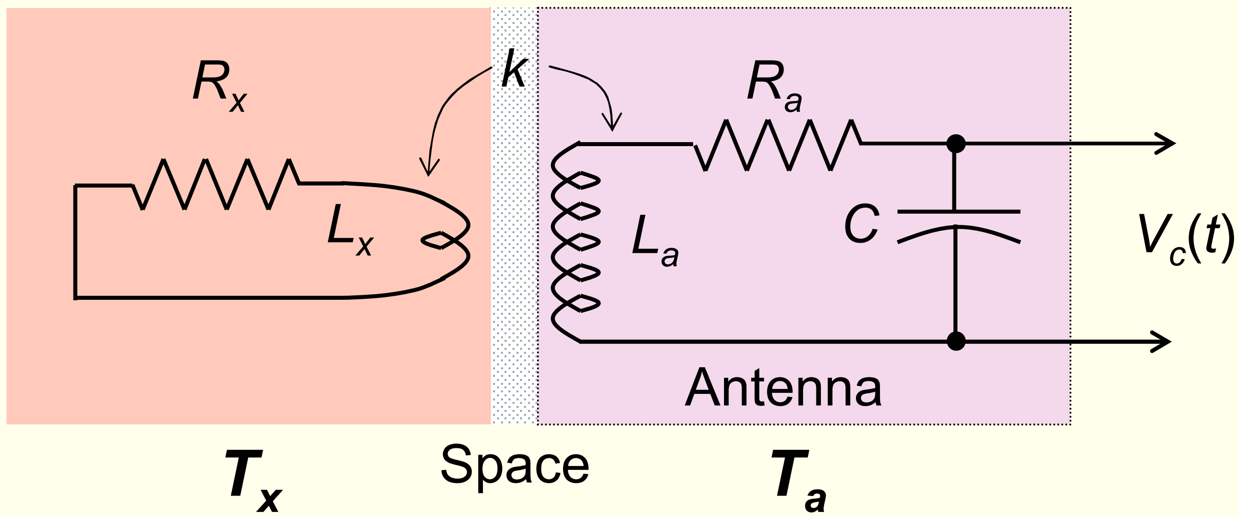


$$\langle V^2 \rangle = \int S_v(f)\,\mathrm{d}f = 4k_B T R \frac{\pi}{2}\frac{f_0}{Q} = \boxed{\frac{kT}{C}}$$

➔ The noise voltage T = 830 K corresponds to RMS voltage of 3 μV at the antenna

Inductively Coupling Johnson Noise Allows Non-Contact Temperature Measurement

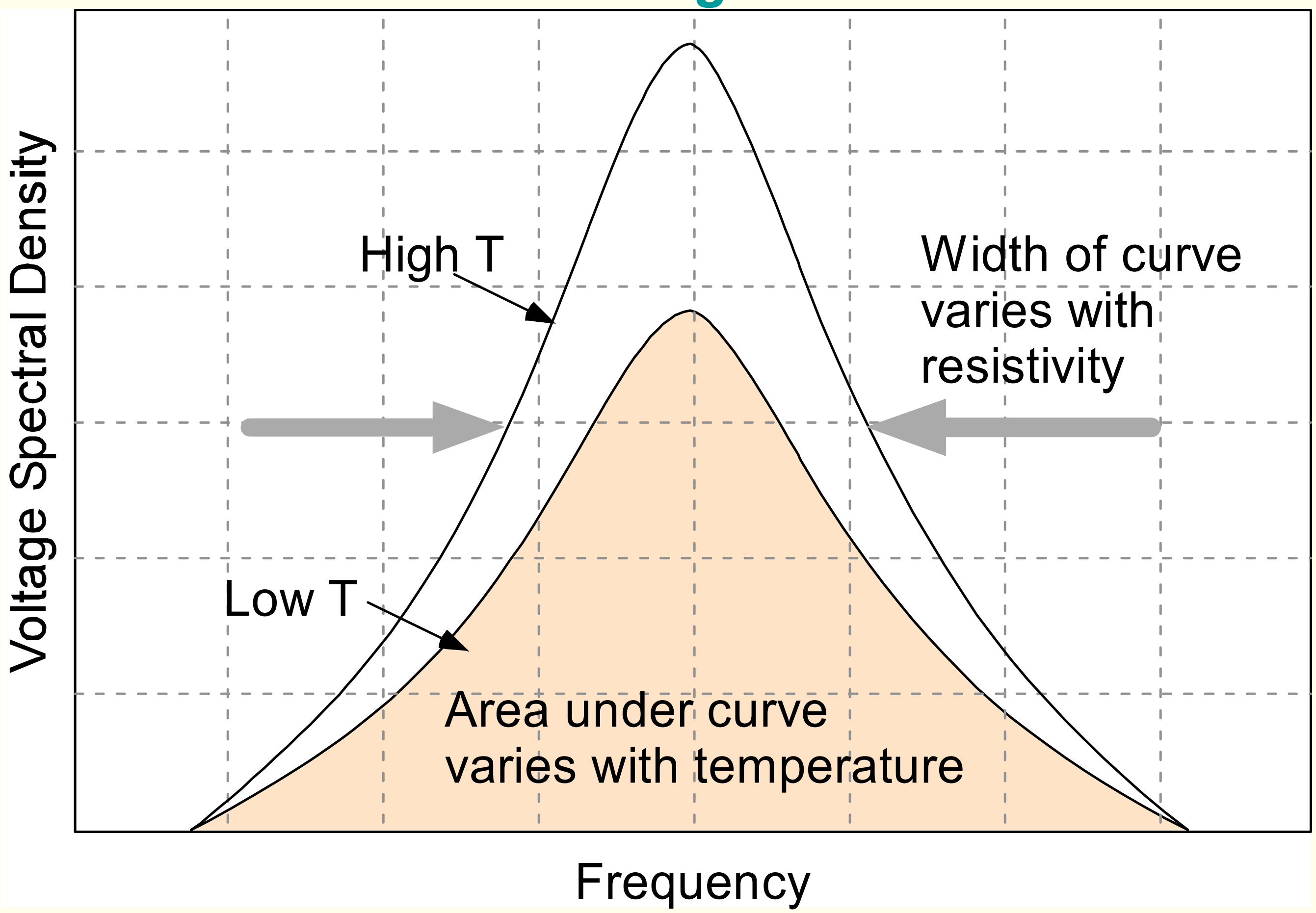
Lumped Parameter Model



Power spectral density (PSD) of V_c varies with resistances, inductances, coupling coefficient, and capacitance. ***Mean-squared voltage across the capacitance is independent of the resistance.***

Integral of Spectral Thermal Noise Voltage Is Proportional to Temperature

Resistance does not change the area under curve



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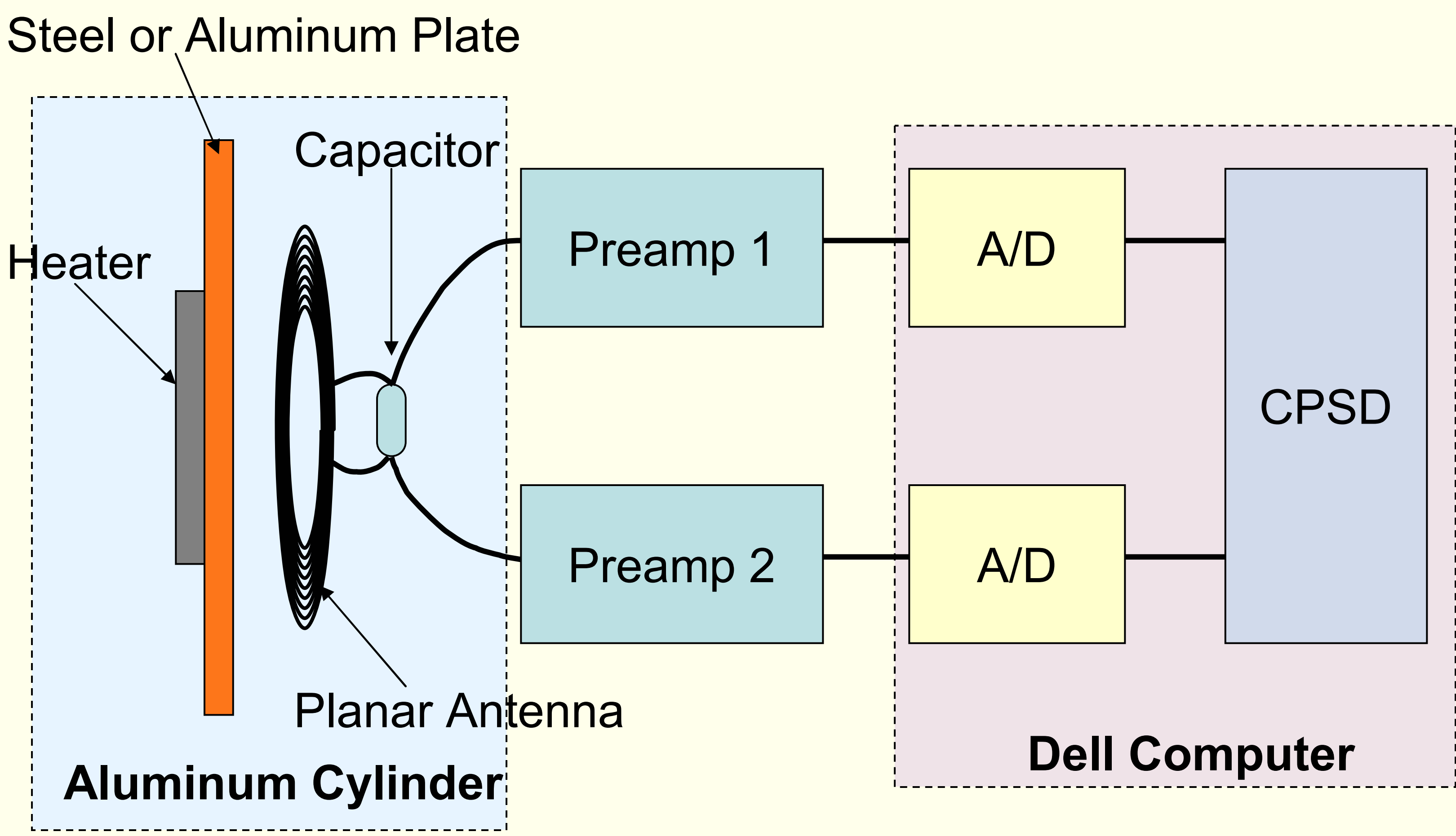
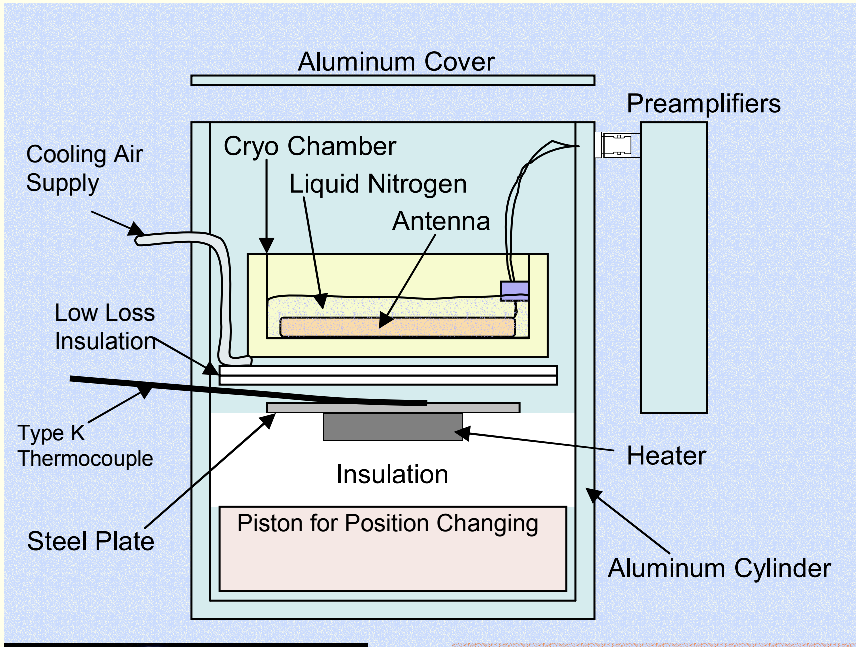
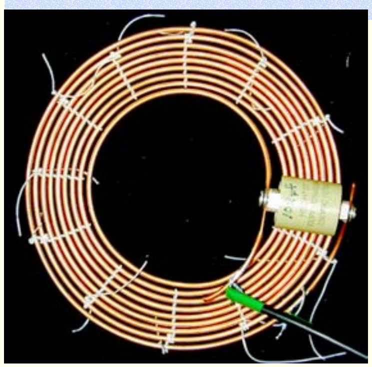
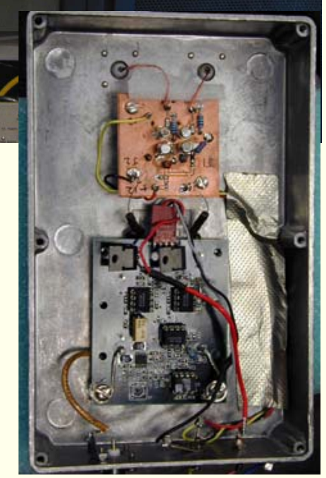
Signal Flow Path in Apparatus



Apparatus: Faraday Shield, Heated Plate, Antenna, Preamps, A/D, LabVIEW







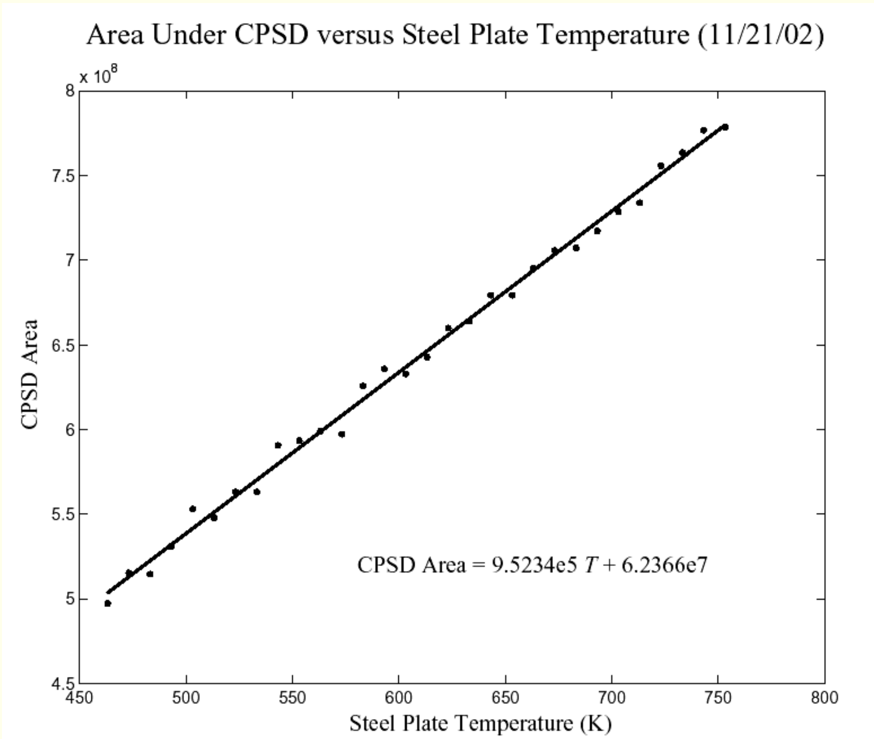
Lower Conductivity Materials Are Easier to Measure Johnson Noise

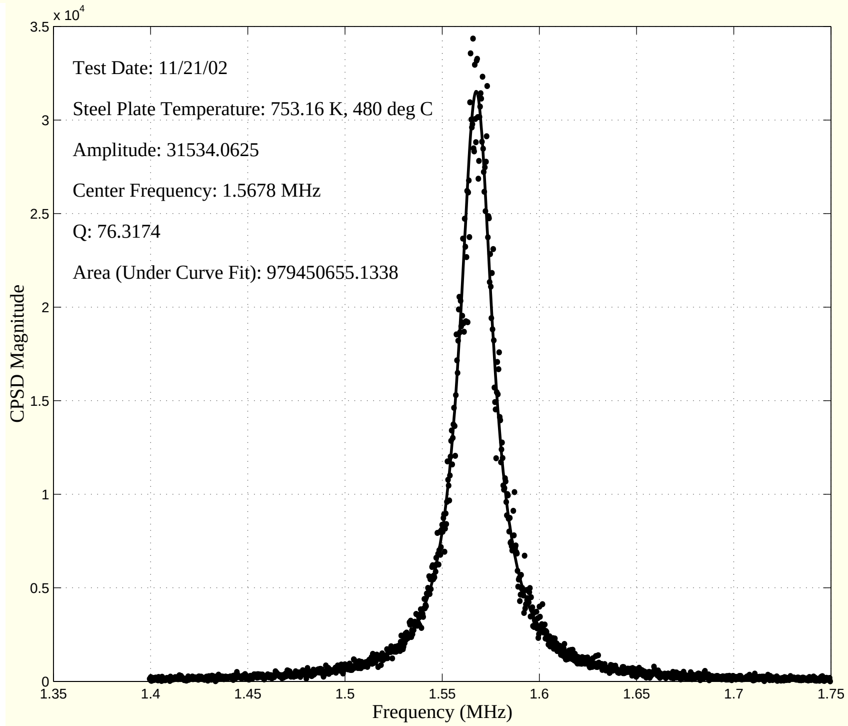
- **Effective surface resistance of aluminum is very low**
- **Square root of difference in conductivity**
- **Factor of 2.5 between aluminum and steel**

Metal	Conductivity [σ] (mhos/m)	Skin Depth [δ] @ 1MHz	Skin Depth [δ] @ 10MHz	Surface Resistance @ 1MHz	Surface Resistance @ 10MHz
Copper	5.8×10^{7}	66×10^{-6} m	21×10^{-6} m	0.26×10^{-3}	0.82×10^{-3}
Aluminum	3.6×10^{7}	83×10^{-6} m	26×10^{-6} m	0.34×10^{-3}	1.1×10^{-3}
Steel	5.6×10^{6}	211×10^{-6} m	67×10^{-6} m	0.85×10^{-3}	2.7×10^{-3}

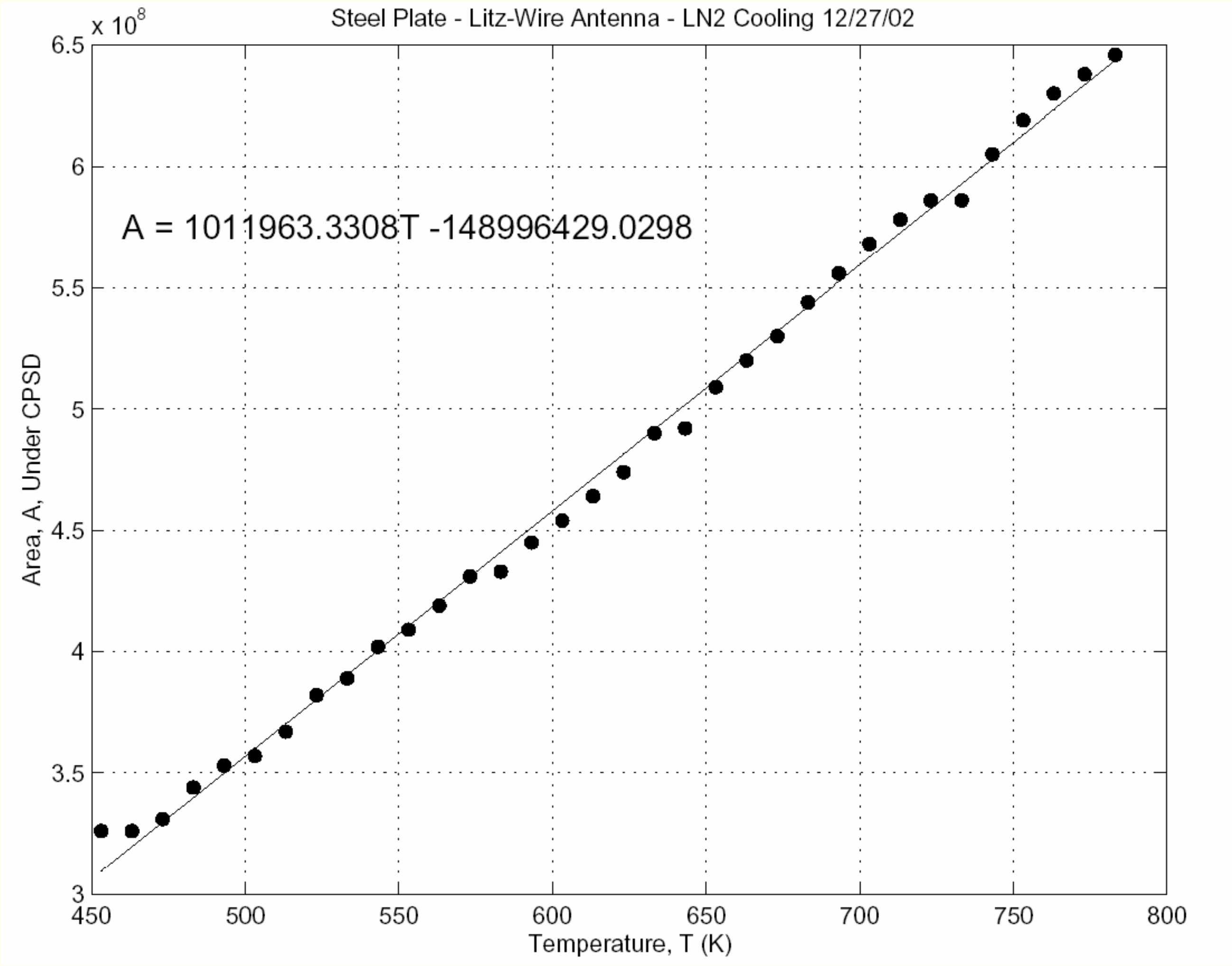
IJNT Temperature Linearly Follows Thermocouple

First Experiment: Copper Tubing, LN_2 Cooled, Steel Plate





Steel Plate with Litz Wire



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The Future….

- MSFC interested in replacing all thermocouples with JNT by integrating resistor with object of interest
- Technical challenges for CJNT and IJNT
  - No showstoppers
  - Physical miniaturization of very high-gain single bandpass electronics (>100dB, end-end coupling)
  - All-JFET preamps are desirable for improved noise and radiation hardness
  - For CJNT, identification of appropriate resistance materials for very high temperatures
  - For IJNT, antenna materials and construction
  - Low power consumption topologies for miniaturized versions


END
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