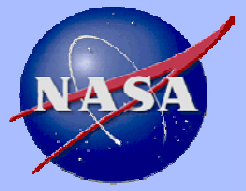


Nondestructive Evaluation Sciences Branch

Structural Health Monitoring with Carbon Nanotube and Graphene Sensors

- Buzz Wincheski[1], Godfrey Sauti[2], John Gardner[2] and Mia Siochi[2]

- NASA Langley Research Center
  - [1]Nondestructive Evaluation Sciences Branch, [2]Advanced Materials and Processing Branch
- NASA Space Technology Research Fellows: [3]University of Notre Dame, [4]Massachusetts Institute of Technology

ASNT Research Symposium 2020

3/25/2020

Overview

- Background
- Sensory Capabilities of Carbon Nanostructures (*CNT* and Graphene)
- Structural CNT composites with Strength to Mass ratio competitive with SOA carbon fiber composites
- Direct Printing of Graphene and CNT sensors on Additively Manufactured components
- Preliminary Test Results
- Future Directions
- Summary

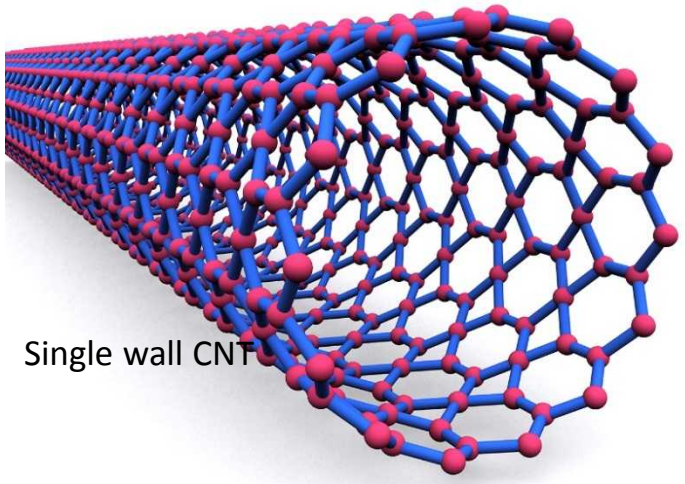
Carbon Nanotubes and Graphene

Nondestructive Evaluation Sciences Branch

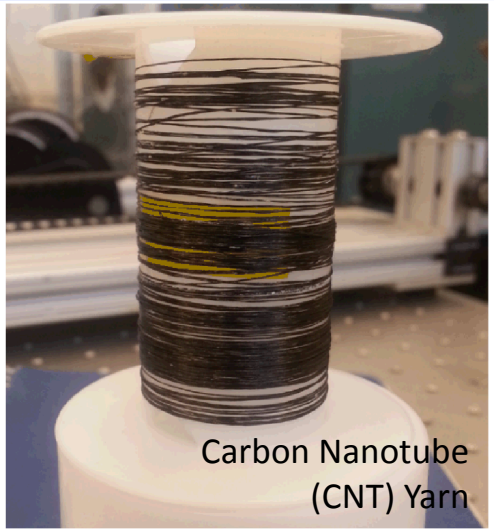
Potential
- Superior mechanical properties at the nanoscale
- Multifunctionality: e.g., electrical and thermal conductivity

Challenges
- Scaling up while retaining material properties
- Handling difficulties

Advantage
- Can be used in 3D printable forms



Single wall CNT



Carbon Nanotube (CNT) Yarn

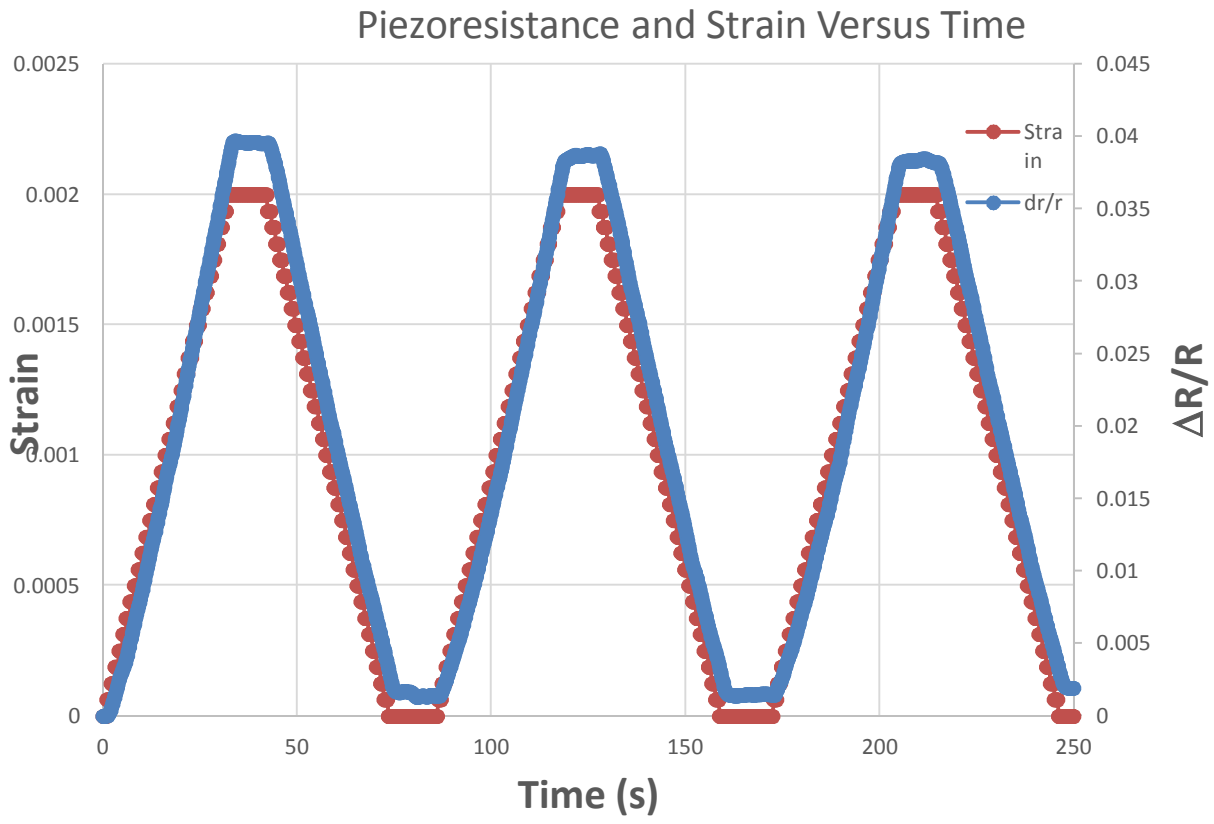
Graphene Oxide (GO)

Image Credits: NASA

Single Strand CNT Fiber, 21 Micron Diameter

Nondestructive Evaluation Sciences Branch

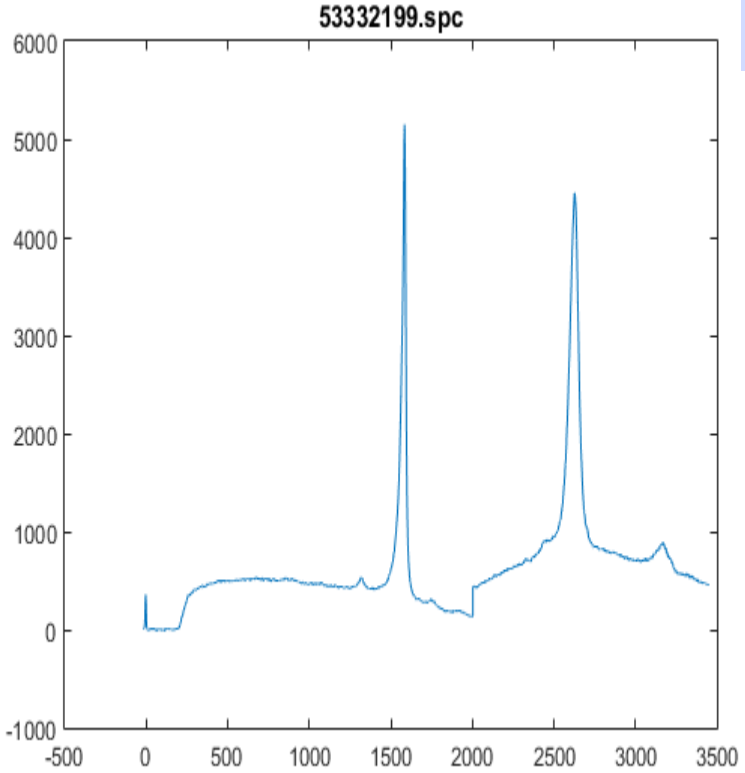
31.6 microamp bias current

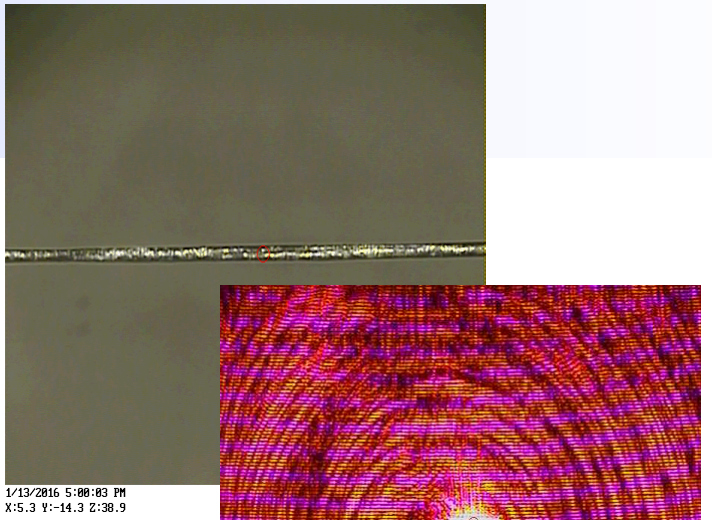


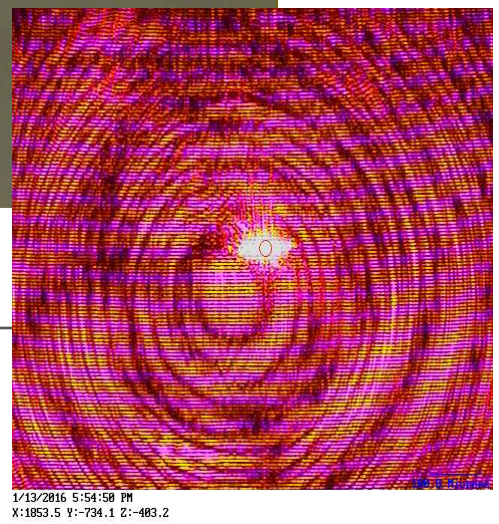
R0 = 66 ohms, Gauge Length = 1”
Gauge Factor = 19 (at 2 millistrain)

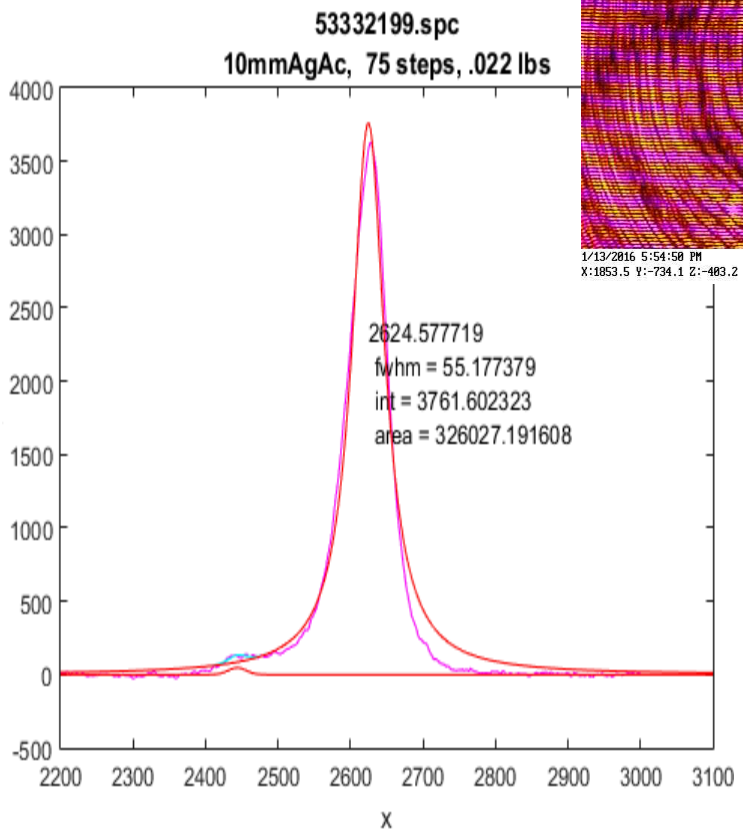
Resistivity = 9 x 10^-5 ohm-cm
Conductivity = 1.1 x 10^4 S/cm

Raman Spectroscopy



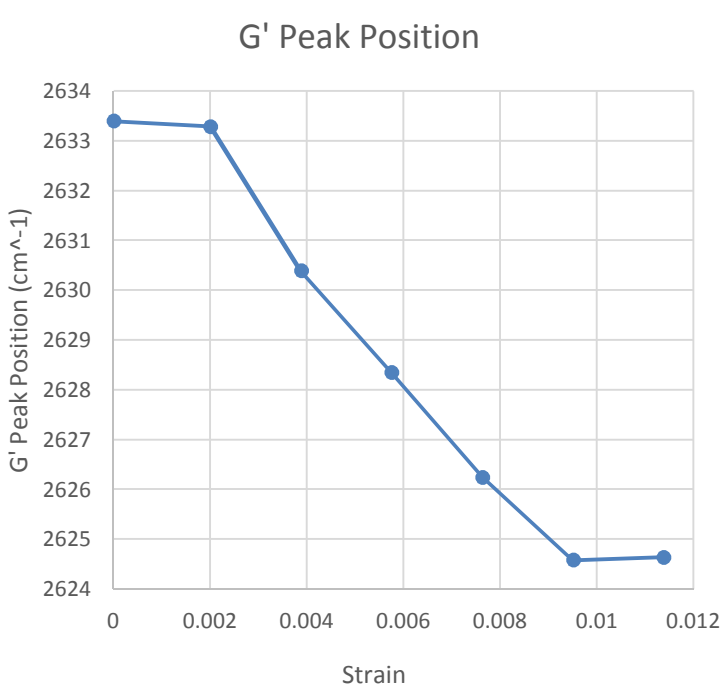


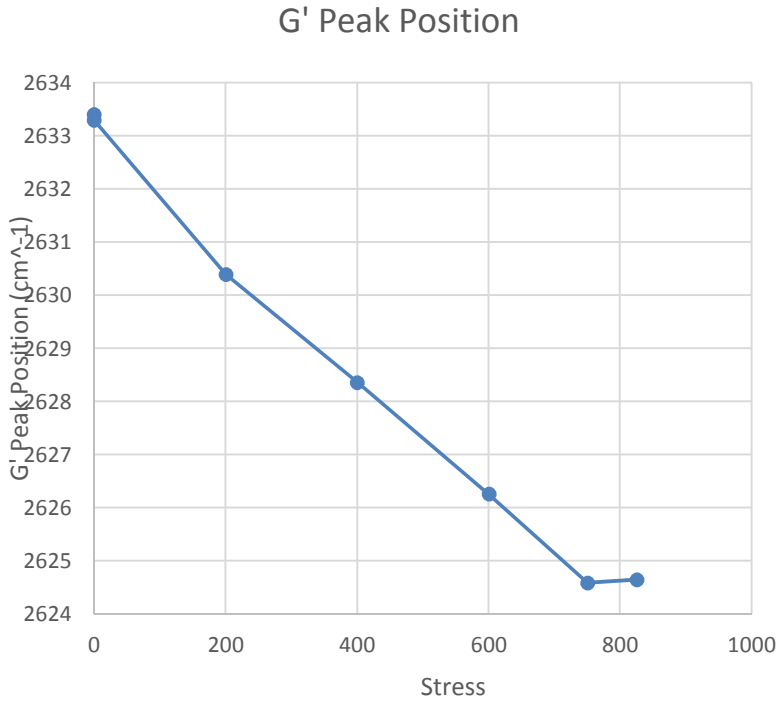




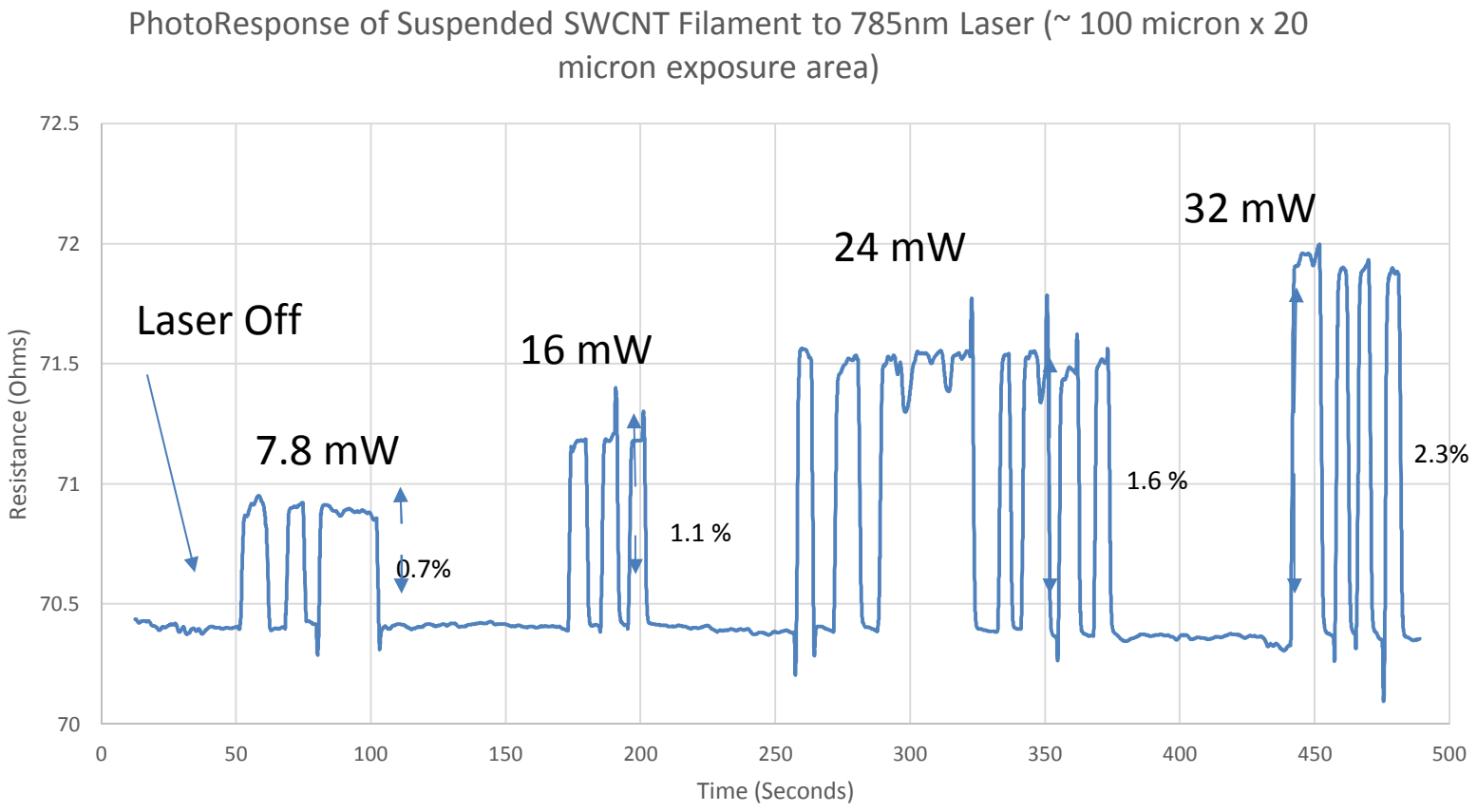
632.8 nm
5.5 mW
5 sec Exposure Length x 5 accumulations

G’ Peak Position Versus Stress and Strain

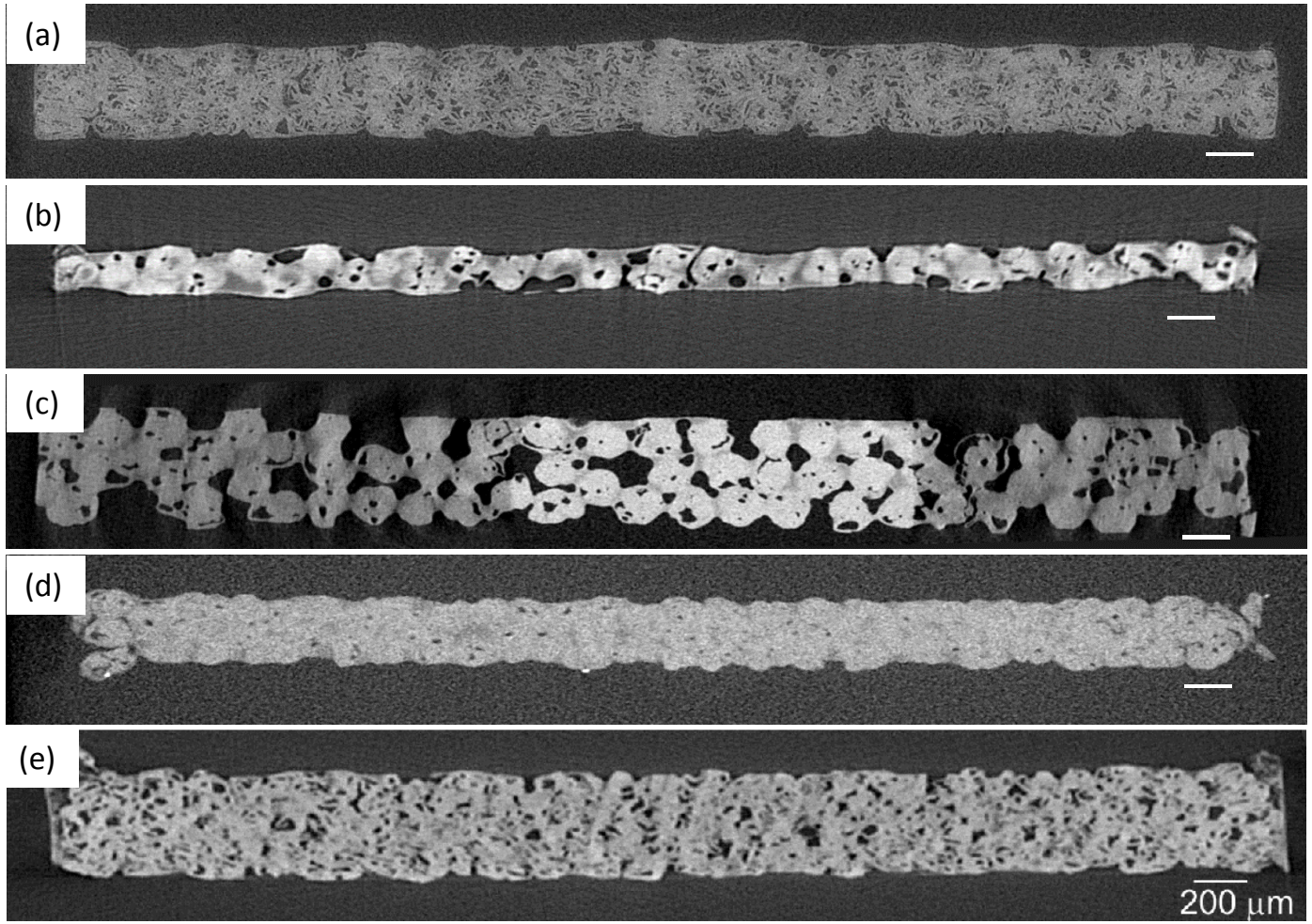




PhotoResponse of CNT Fiber



CNT Composites



Cross sectional X-ray CT images of unidirectional CNT yarn/API-60 composites prepared at various processing conditions such as (a) 2 layers, 2.2 lbf in winding tension, and 200 psi in cure pressure, (b) by using prepreg, 2 layer lay up, and 200 psi in cure pressure, and (c) 2 layers, 3.0 lbf in winding tension, and autoclave cure. (d) Cross sectional X-ray CT image of unidirectional CNT yarn/cyanate ester composites prepared with 2 layers of CNT yarn at 3.0 lbf of winding tension and 1500 psi of cure pressure. (e) Cross sectional X-ray CT image of unidirectional CNT yarn/cyanate ester composites prepared with 2 layers of 2 ply CNT yarn at 1.0 lbf od winding tension and 300 psi of cure pressure.

Eddy Current Conductivity of CNT and Carbon Fiber Composite

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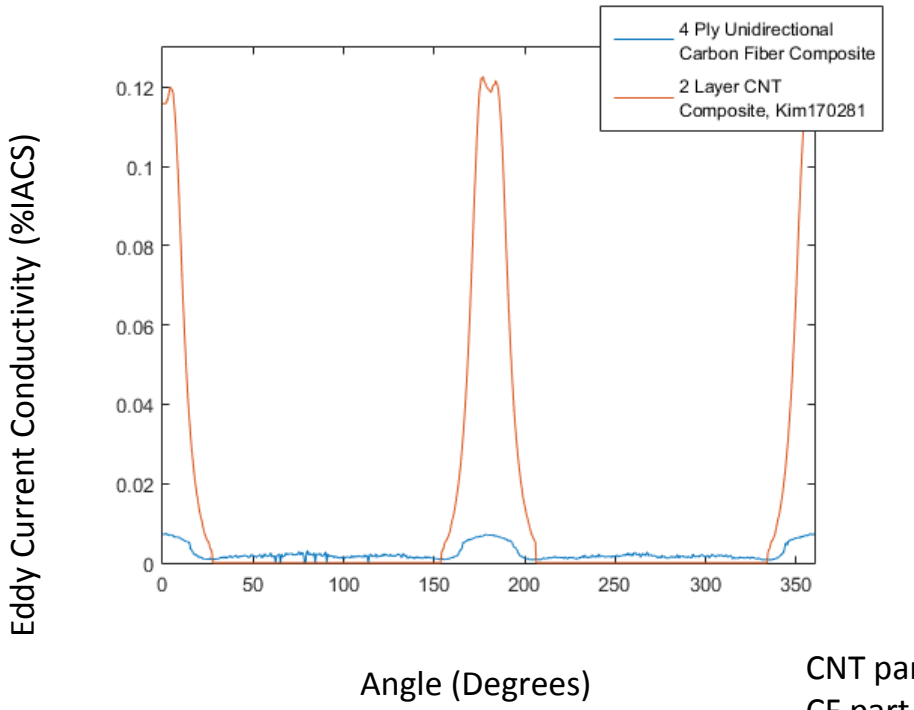


$$J_x = J_0 e^{-(x/\delta)}$$

$$\delta = 1/\sqrt{\pi f \mu \sigma}$$

$\delta(f = 10MHz, \sigma = 0.12\ \%IACS) = .603\ mm$

$\delta(f = 10MHz, \sigma = 0.007\ \%IACS) = 2.5\ mm$

CNT part thickness = 0.419 mm

CF part thickness = 0.841 mm

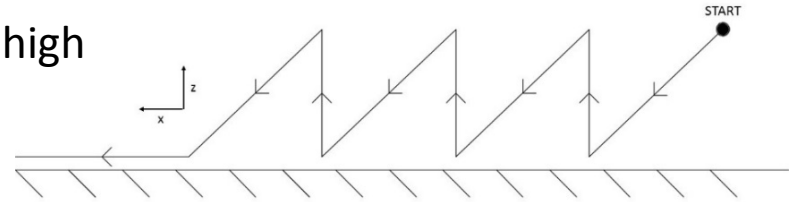
Directional conductivity measured with inductive probe at 10 MHz

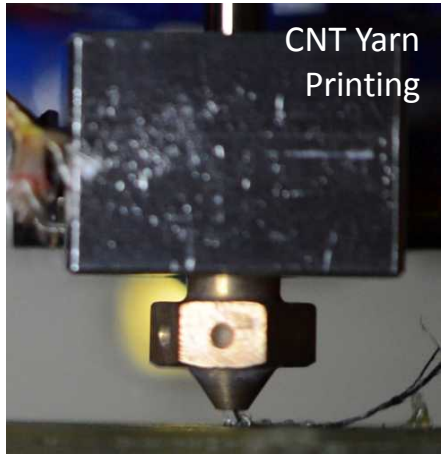
CNT and Reduced GO Printing

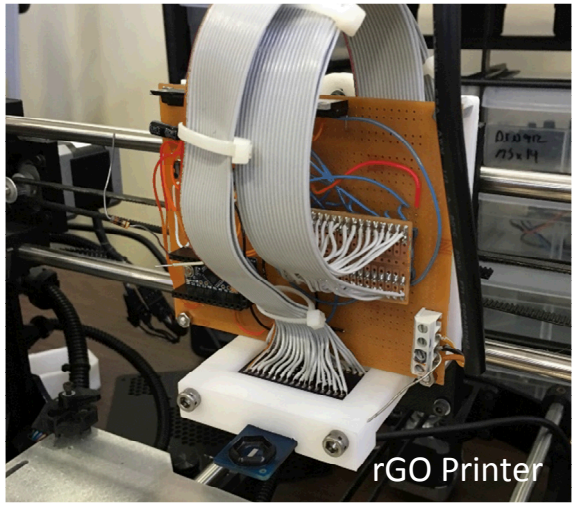
CNT Yarn Printing

- High density CNT yarn coated with polymer
- Selective compaction
- CNT compliance allows for high fidelity printing

Selective Compaction







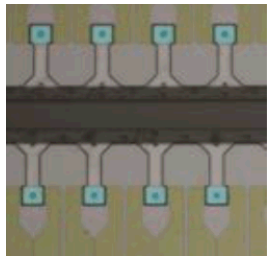


Image Credits: NASA

Reduced Graphene Oxide (rGO) Printing

- Developed cooperatively between NASA and MIT
- GO/water suspension
- Spray deposition
- Reduced via heat and ascorbic acid

ecoDemostrator Flight Test

Nondestructive Evaluation Sciences Branch

Overview

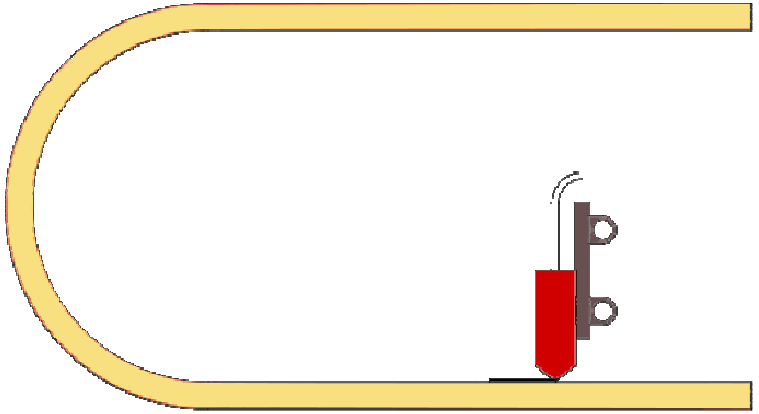
- Print CNT and rGO sensors on flight article
- Collect data during flight
- Test survivability and response of nanomaterial sensors

Image Credit: Boeing

Boeing 777 ecoDemonstrator

Challenges

- Unique printing parameters for rGO and CNT
- Geometric constraints: printing in constrained spaces
- In-situ post-processing



Print substrate geometry

Image Credits: NASA

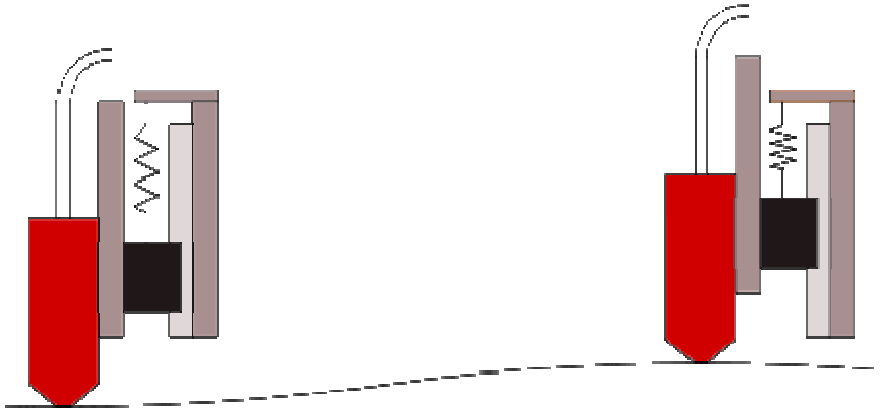
CNT Printing

Compliant Toolhead

- Tool suspended by springs
- Mitigates issues caused by uneven surfaces or machine accuracy

Sensor Parameters

- CNT Yarn
- Geometry: 32 line raster pattern
- Resistance: ~50 Ω



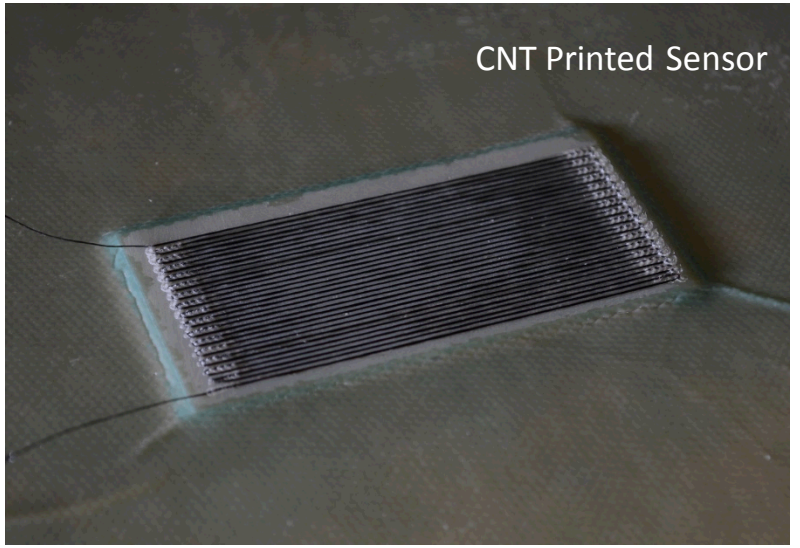
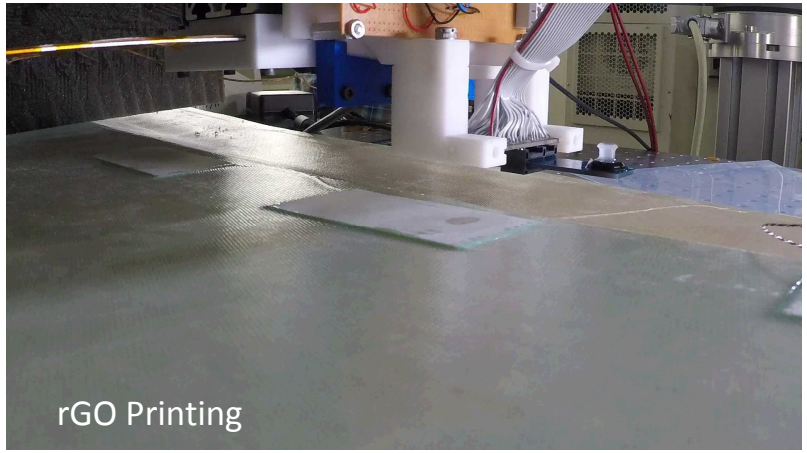


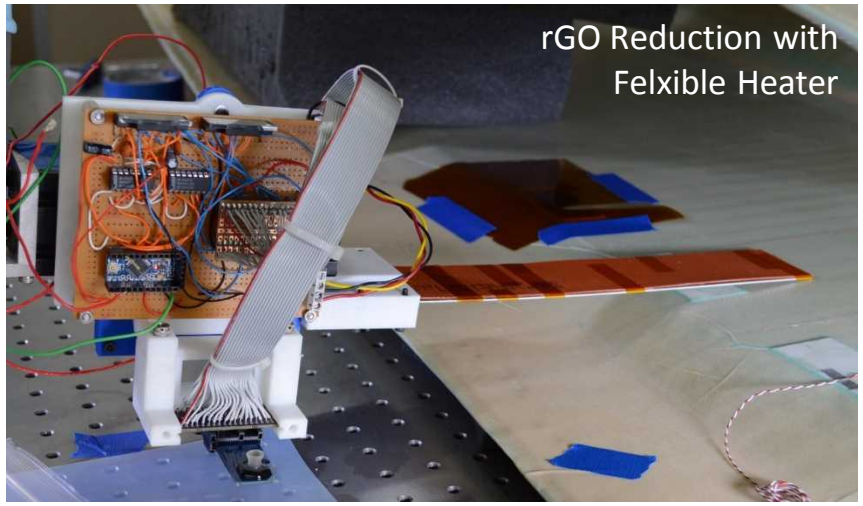
Image Credits: NASA

rGO Printing

Sensor Parameters

- Geometry: 10 mm x 3 mm print area
- Flexible heating plate for rGO reduction
- Resistance: ~5 kΩ





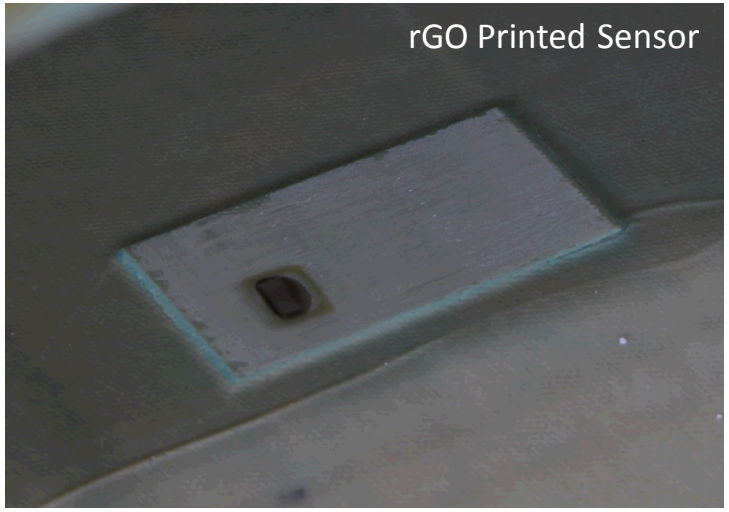
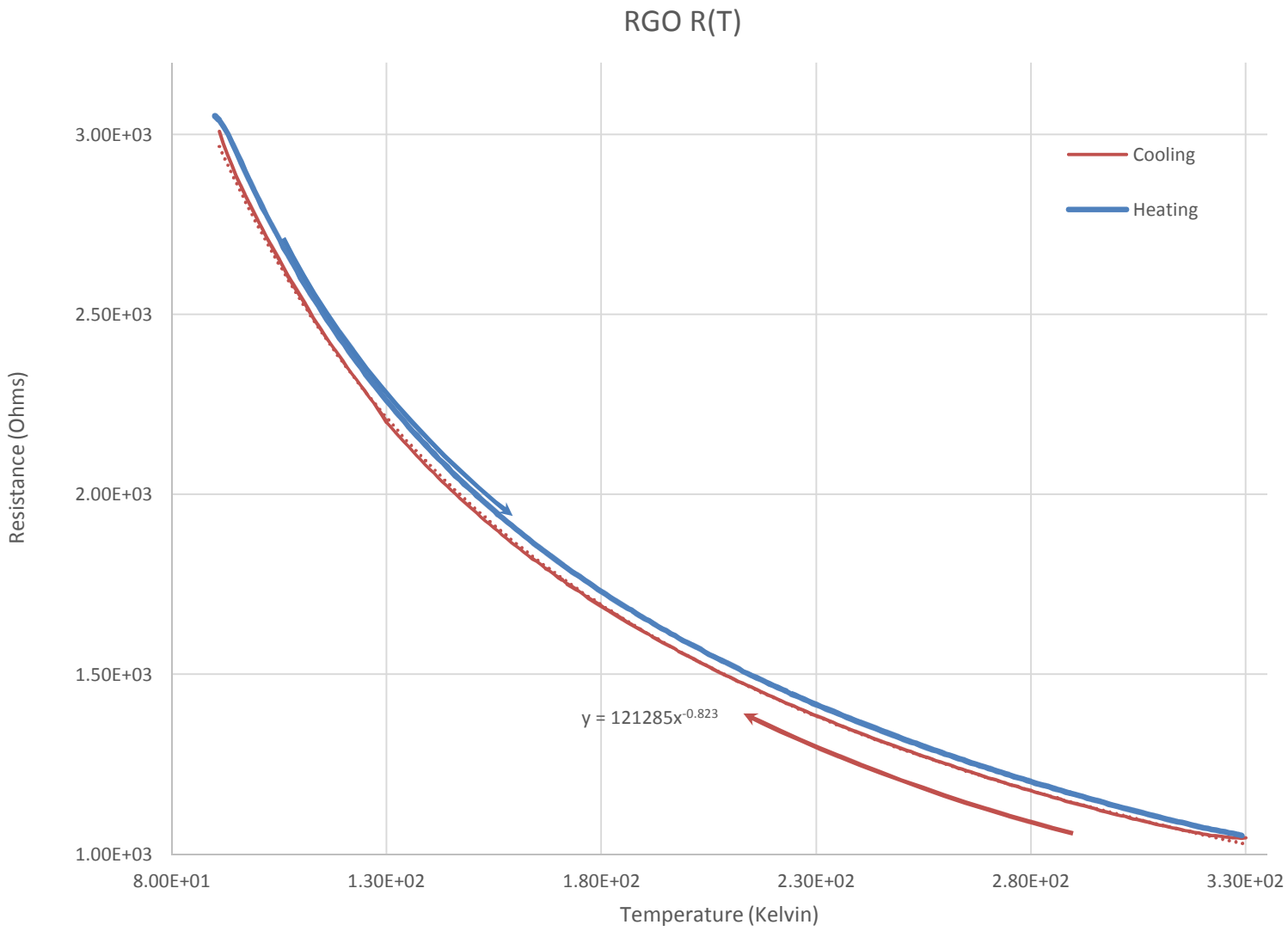


Image Credits: NASA

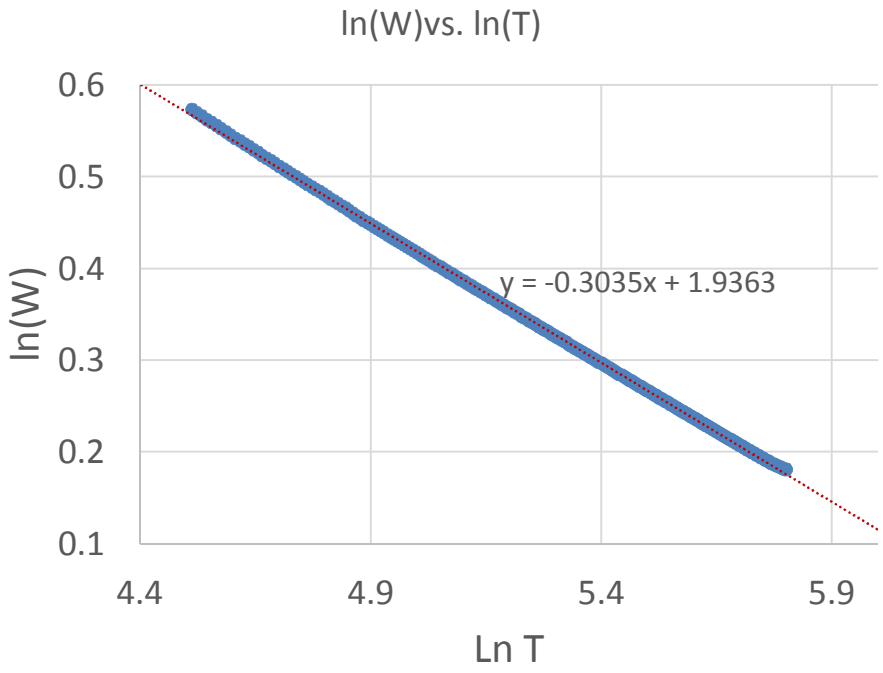
Temperature Dependent Resistance of RGO Sensors: Hopping Conduction



$$R = R_0 \exp\left[\left(\frac{T_0}{T}\right)^p\right], p = \frac{1}{1+d}$$

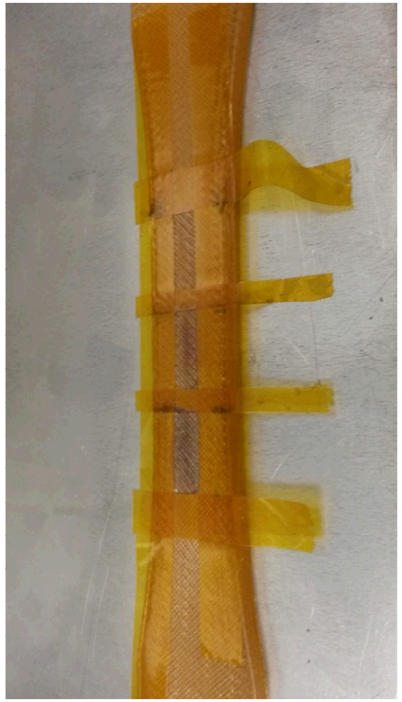
$$W = \frac{d(\ln R(T))}{d(\ln T)}$$

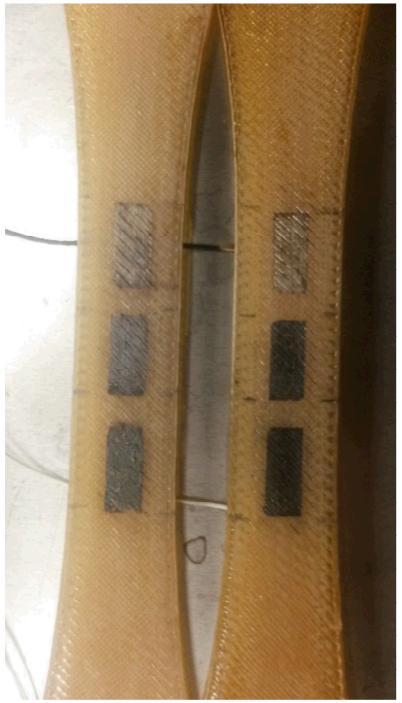
$$\ln W = A - p\, ln(T)$$

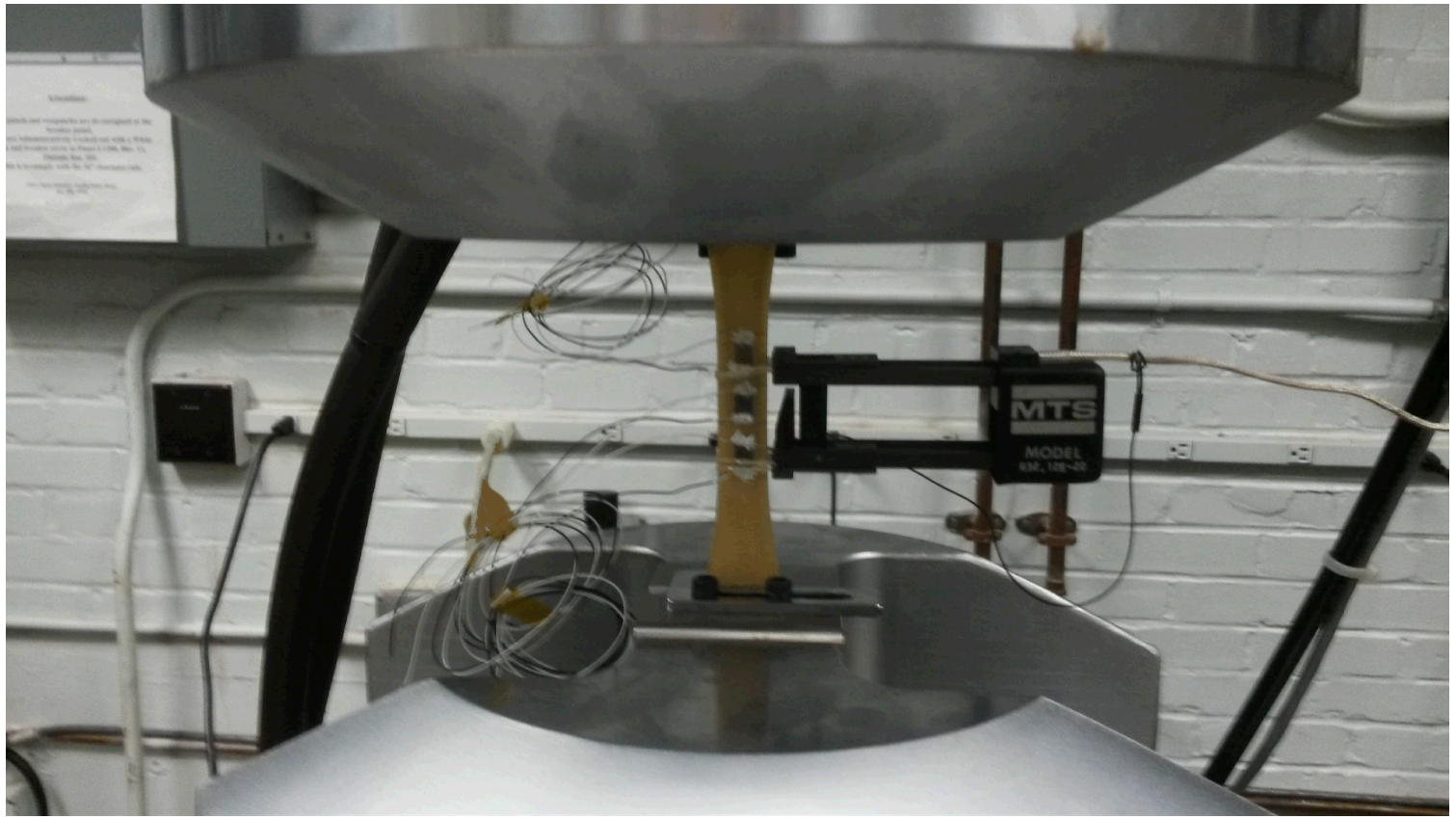


$$d = \frac{1}{p} - 1 = 2.29$$

Piezoresistance Measurements

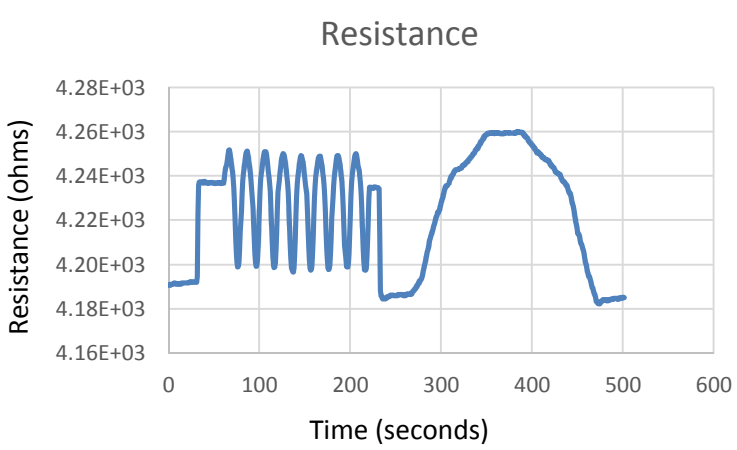




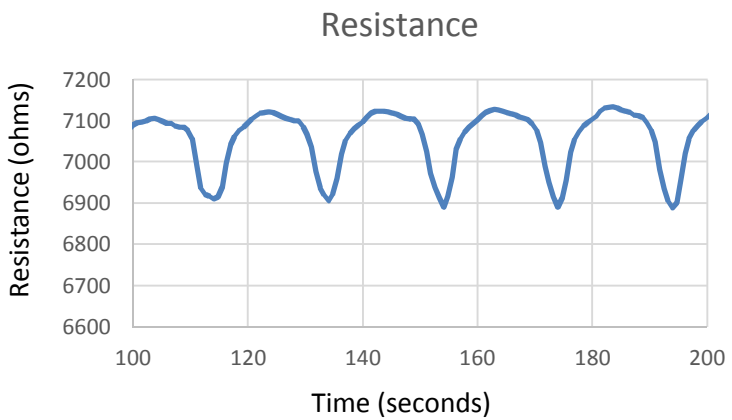


Strain Tests for RGO Sensors Printed on Ultem

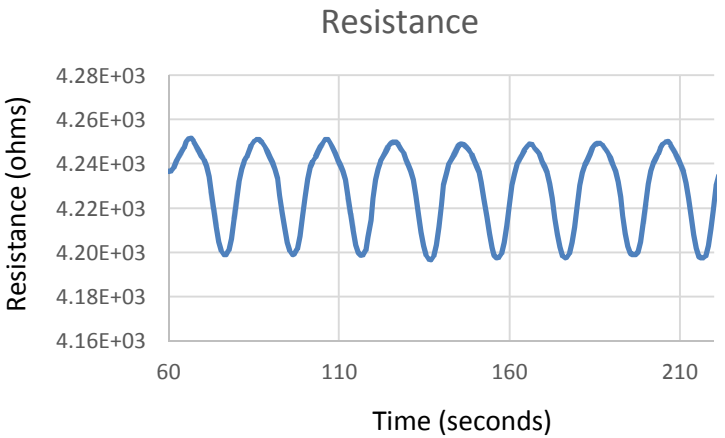
Nondestructive Evaluation Sciences Branch

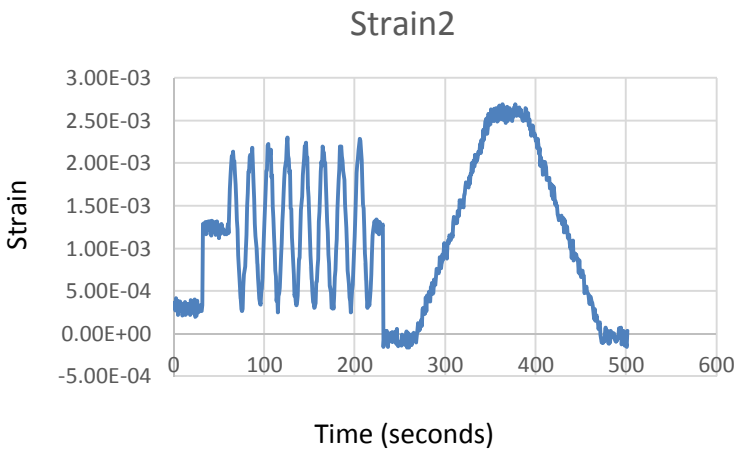


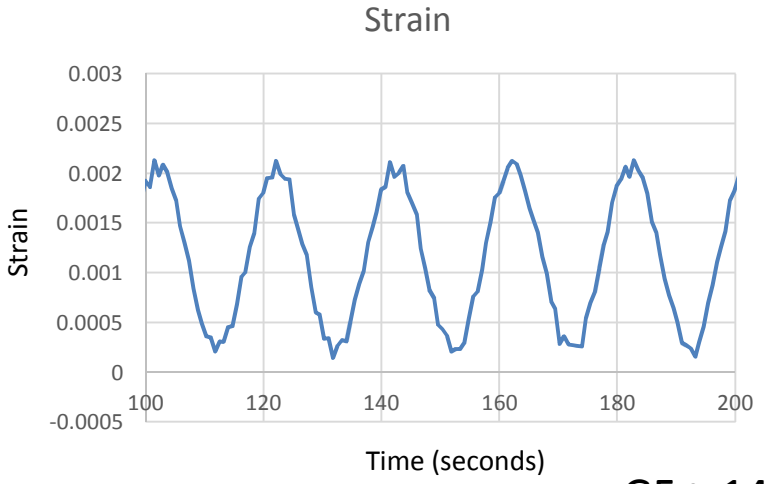
Graphene2 Sensor1



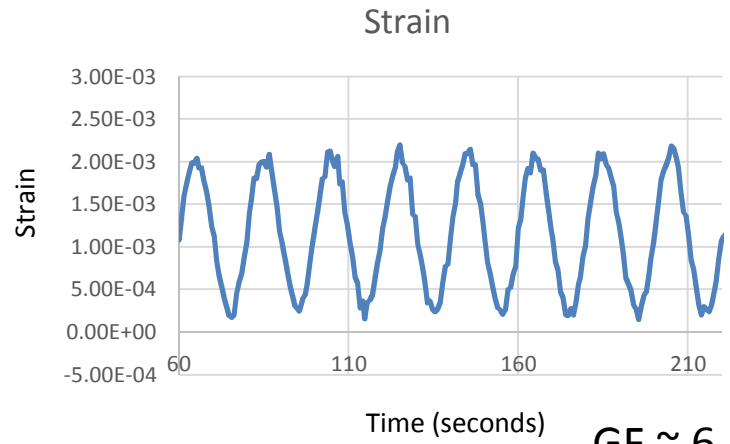
Graphene2 Sensor2







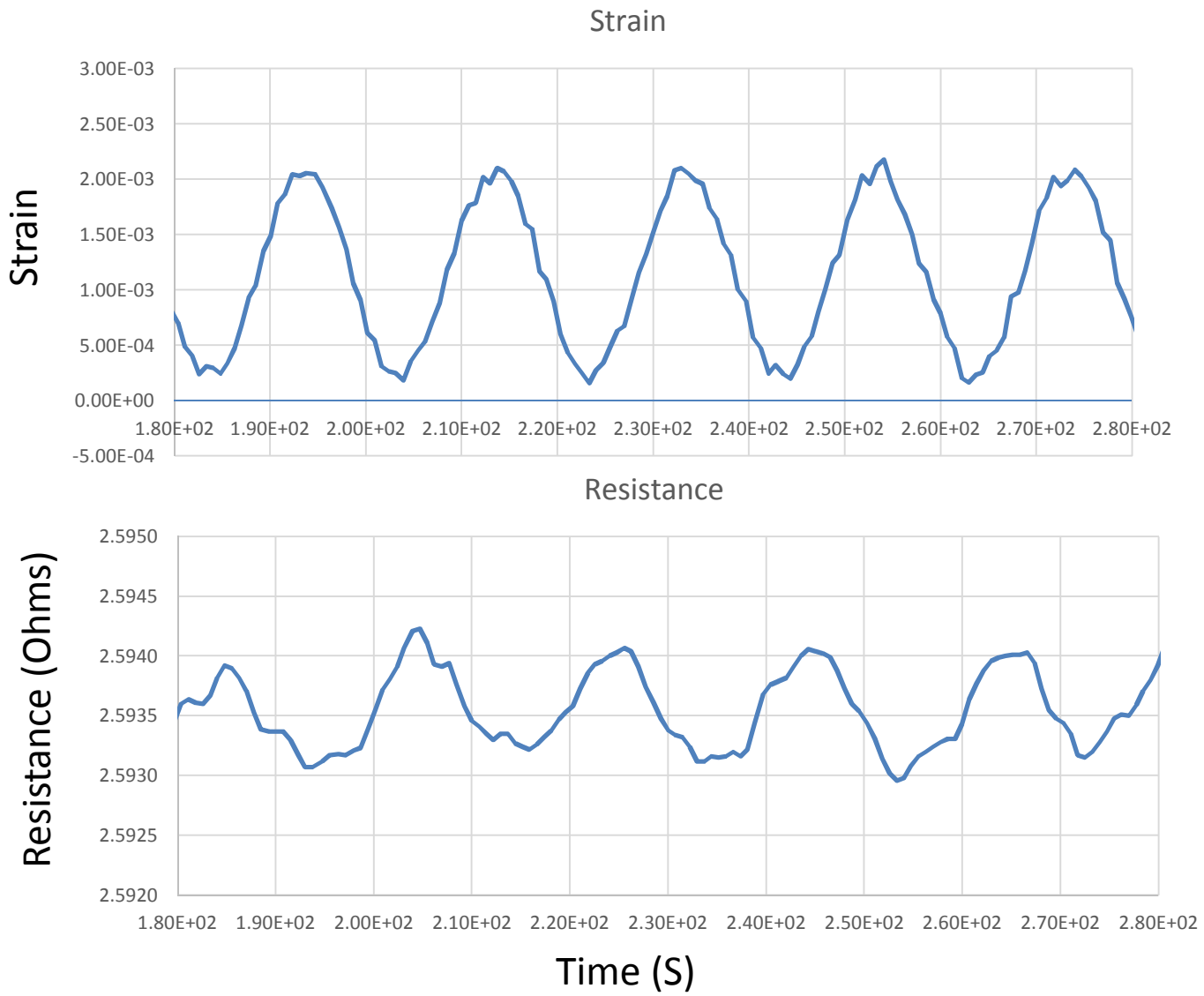
GF ~ 14



GF ~ 6

Piezo-Resistance of CNT Fiber

Nondestructive Evaluation Sciences Branch



Wireless Strain Sensors for Flight Testing

Nondestructive Evaluation Sciences Branch

Phase III SBIR with Invocon Technologies for procurement of wireless DAQ devices for flight testing.

11 bit DAQ sensors have completion bridge wiring for RGO, CNT and commercial foil strain gauges. Gains set to accommodate anticipated temperature response of sensors.

Data acquisition rate fixed at 25 Hz for all sensors.

RGO and CNT sensors printed directly onto flight test article.

Sensors located in inaccessible area, wireless communication and self-powering required.

DAQ devices ~ 1.75” x 1.5” x 0.2” with 10 gm mass.

SAFT LSH20, 3.6V lithium-thionyl chloride (Li-$SOCl_2$) Battery.
34mm diameter x 61.5mm height (D-size) with 100 gm mass.
Operating temperature range -60 °C to +85 ° C.

Wing Panel

- Wing leading edge panel
- Sensor orientation
  - Both CNT sensors lateral
- Commercial strain gauges added as control
- Data acquisition system
  - Wireless interrogation

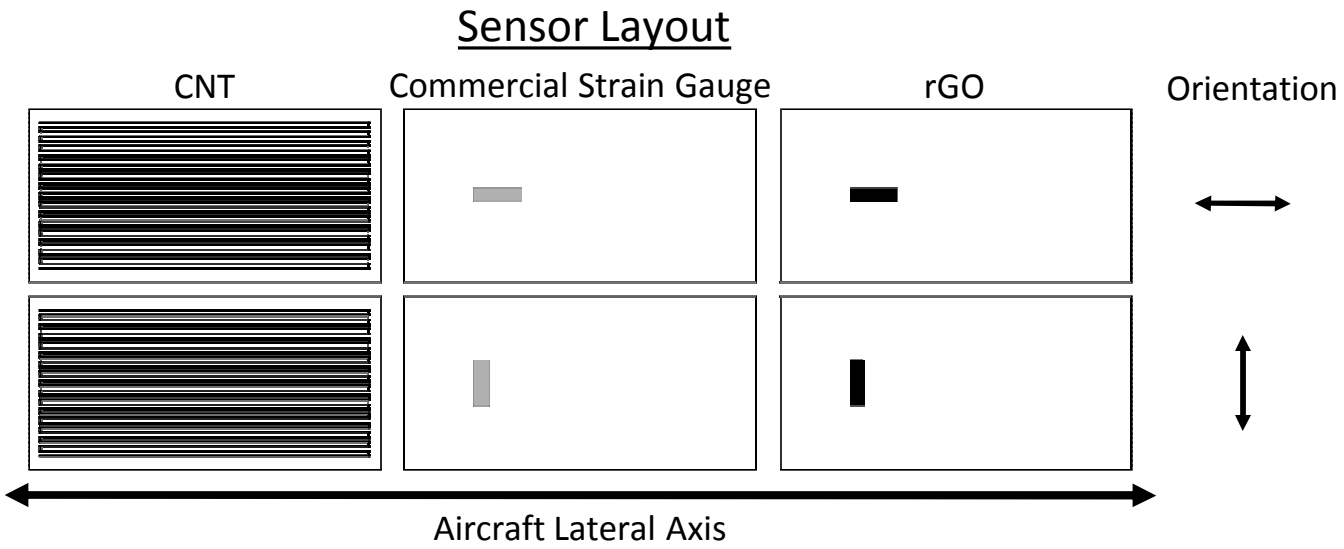
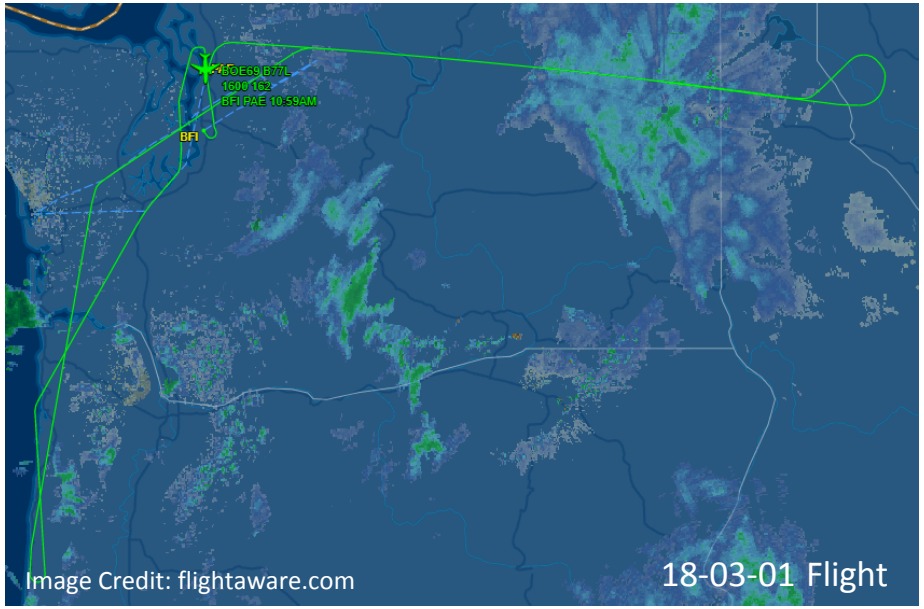
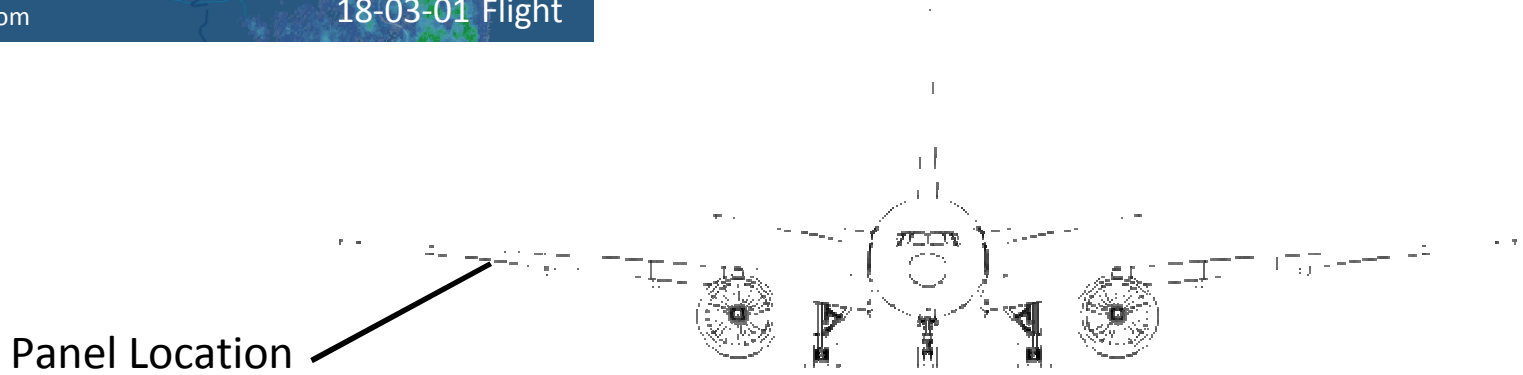


Image Credits: NASA

Flight Test Overview

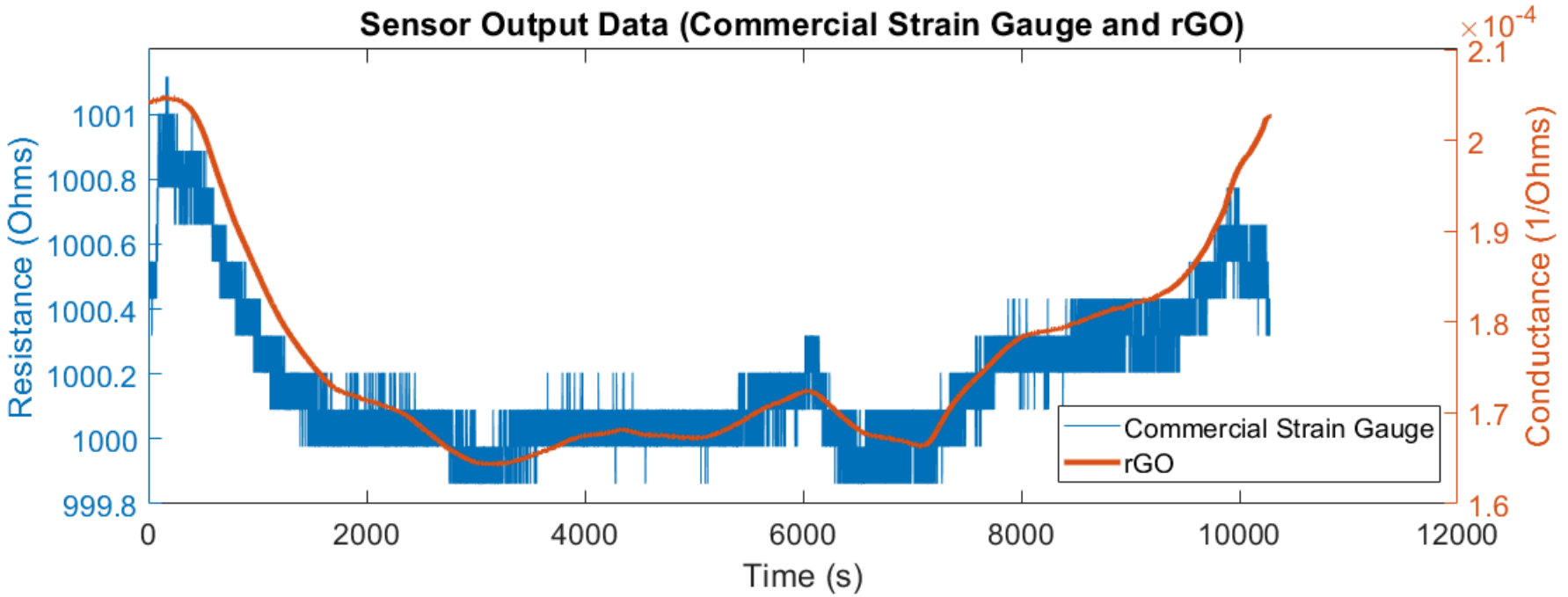


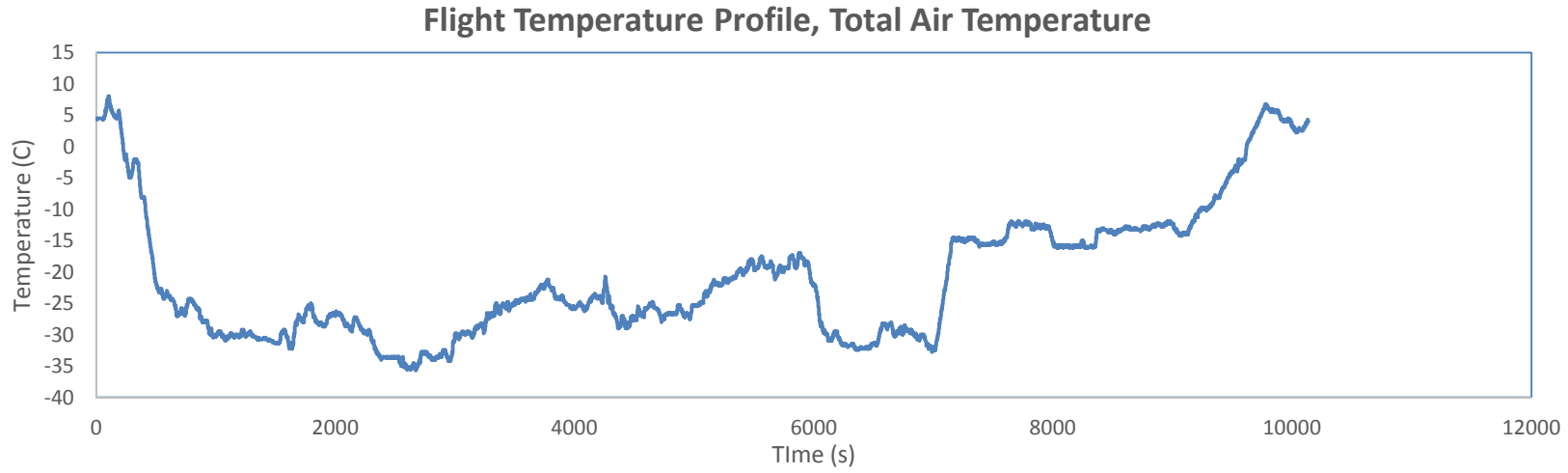
- Sensors printed on wing panel
- Data analyzed for three flights over one week
  - March 1 data shown
- Altitude up to 43,000 ft (~13 km)
- Correlate sensor data with strain and temperature



Collected Data – rGO

3/1/2018 Data

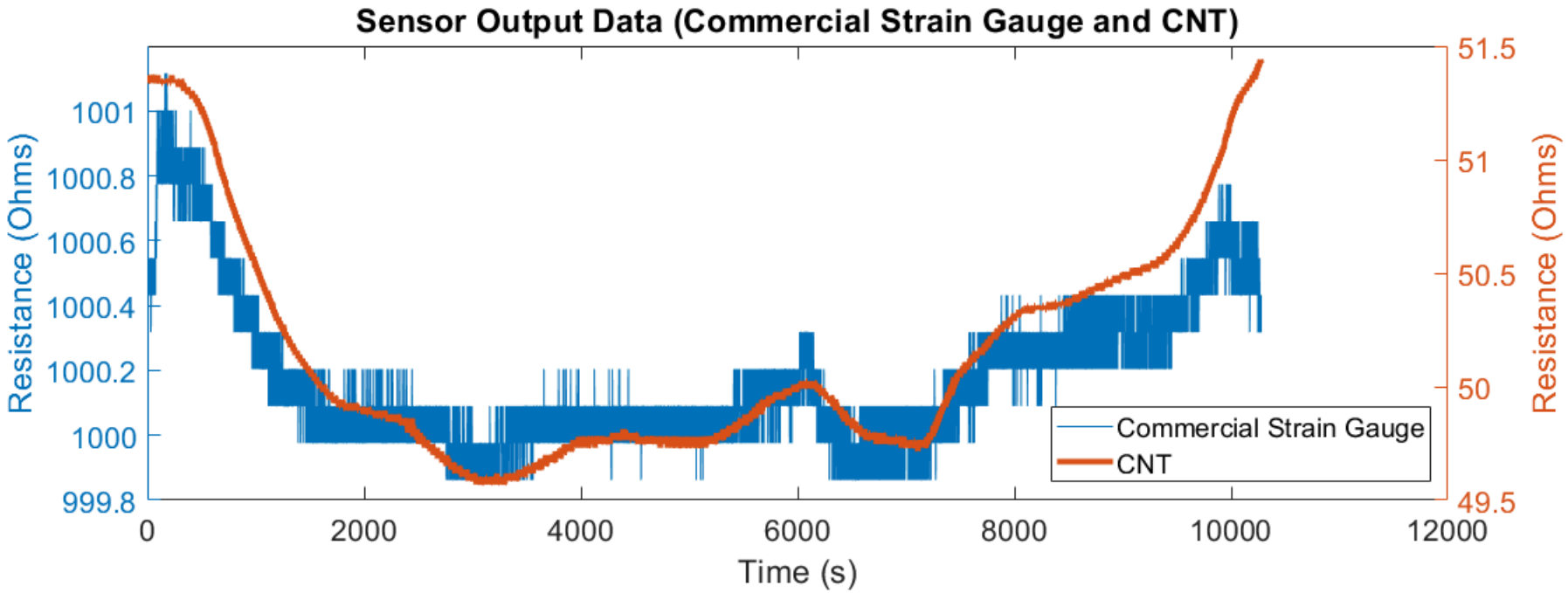


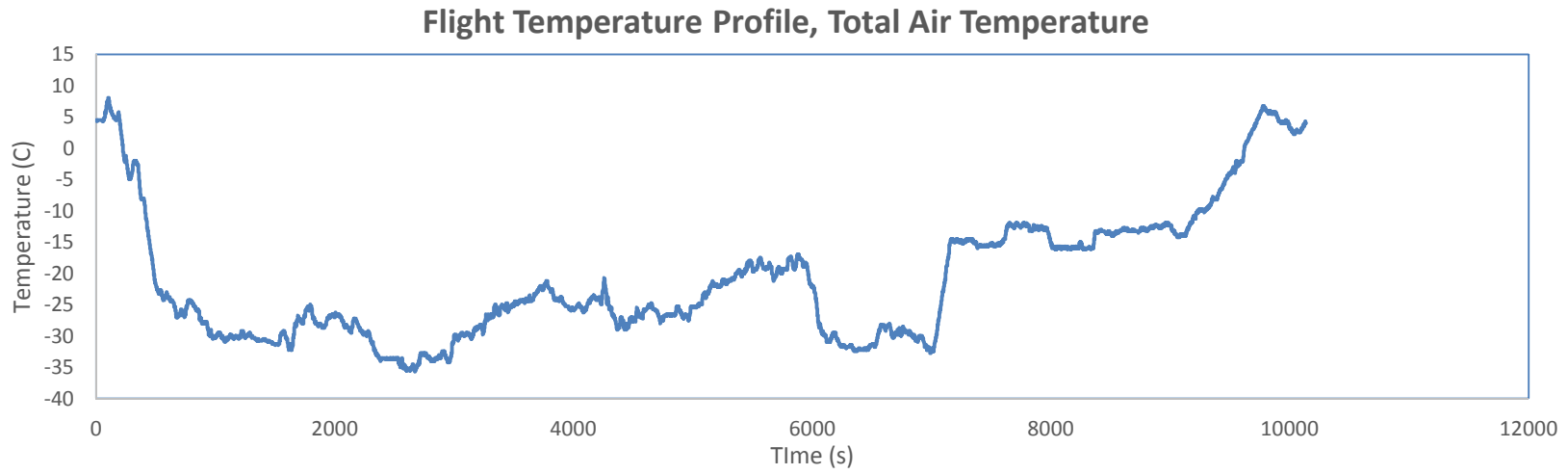


Collected Data – CNT

Nondestructive Evaluation Sciences Branch

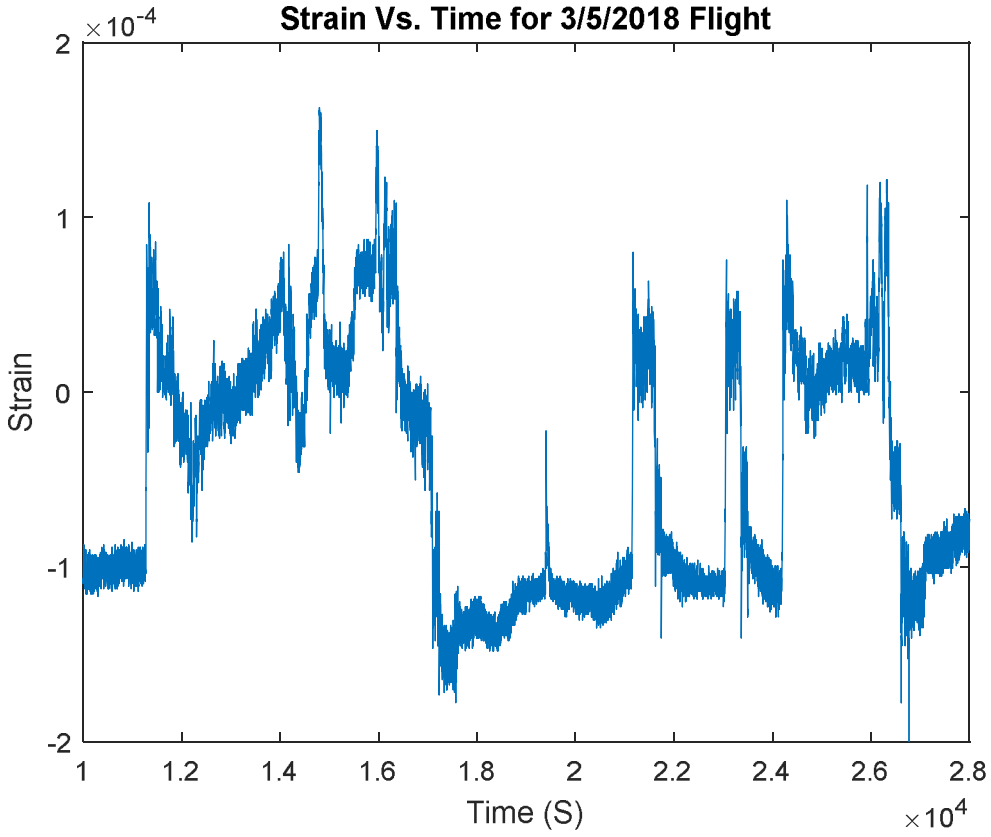
3/1/2018 Data



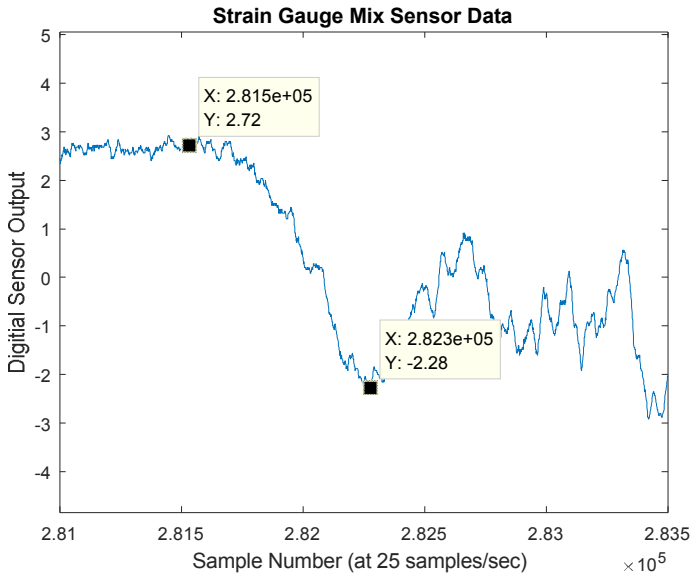


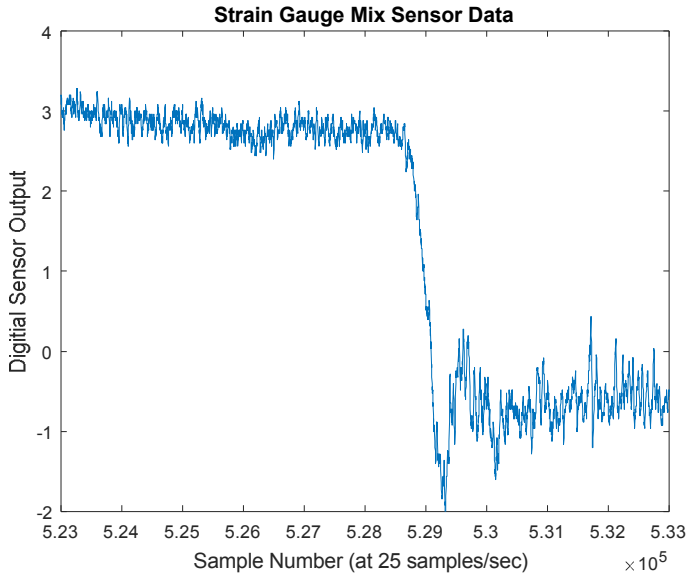
Processed Foil and RGO Strain Gauge Data 3/5/2018 Flights

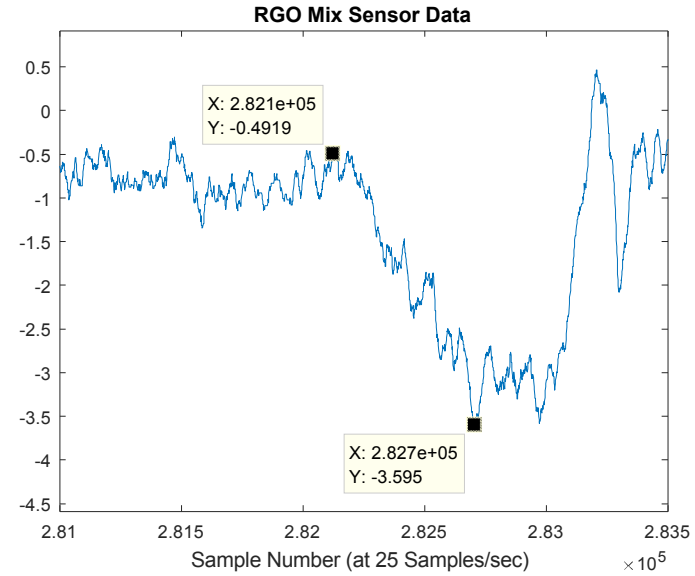
Nondestructive Evaluation Sciences Branch

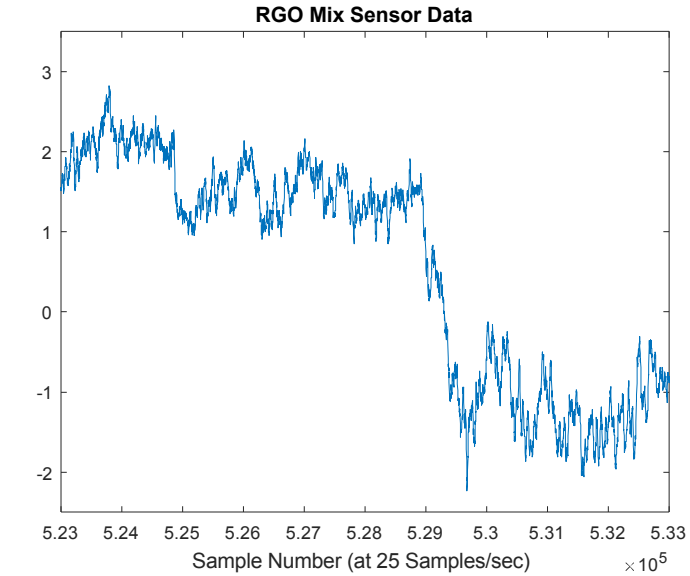


$$\epsilon = \frac{(\frac{\Delta R_1}{\mathrm{R}} - \frac{\Delta R_2}{\mathrm{R}})}{G(1+\nu)}$$

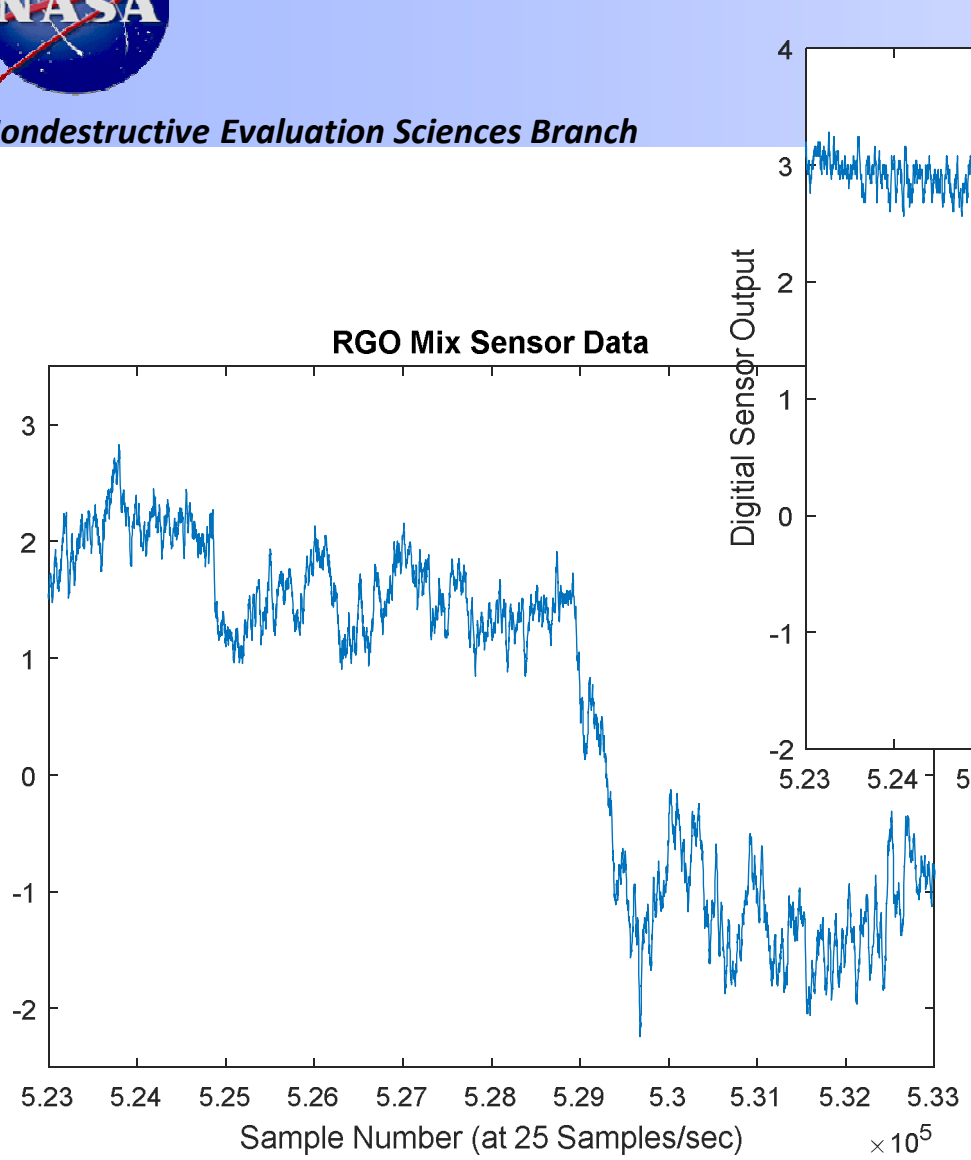


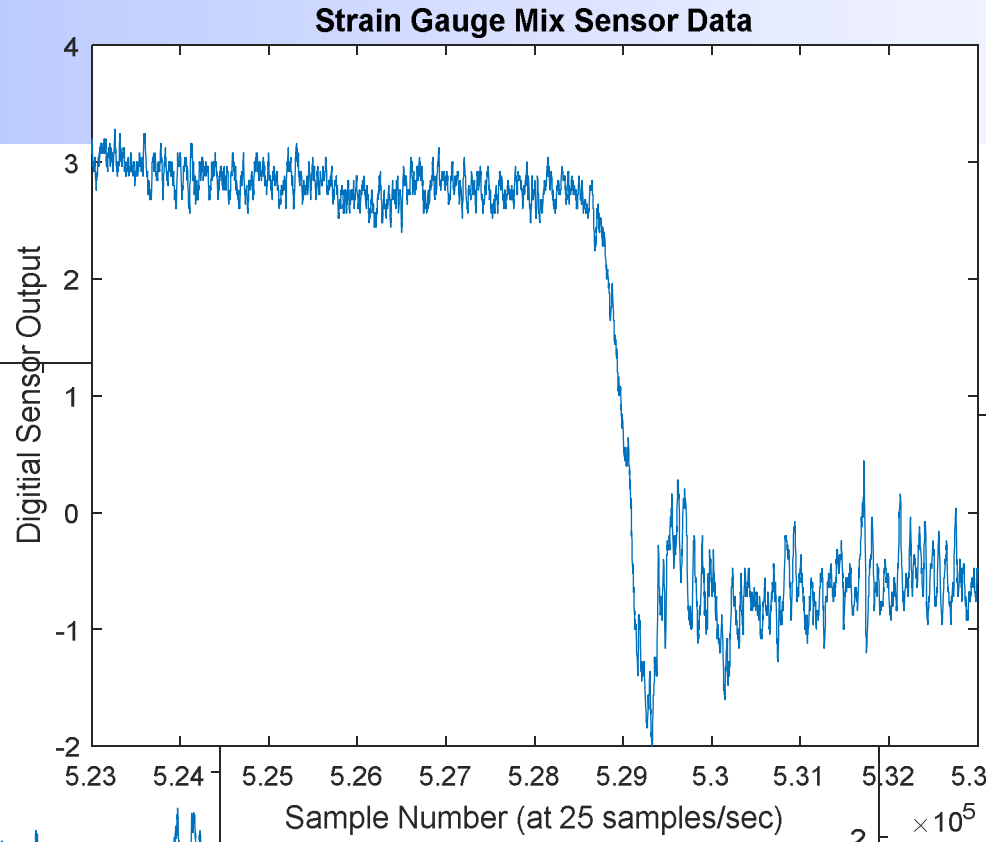


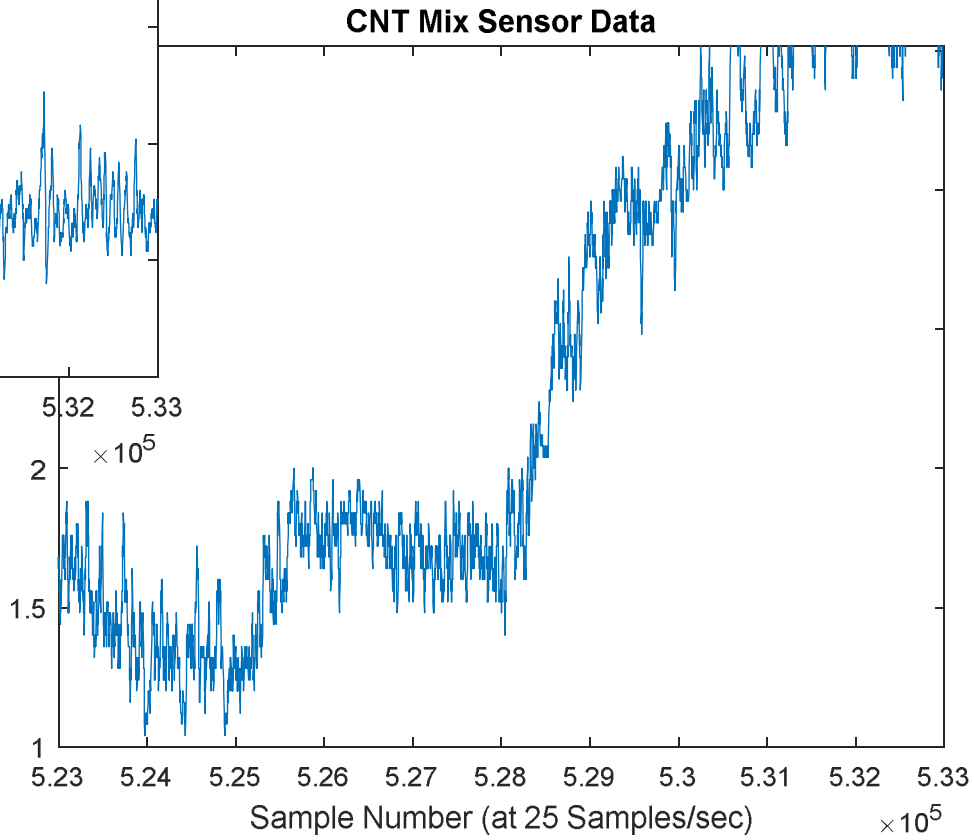




Foil Strain Gauge Vs. RGO Sensor and CNT Sensor: Second lift-off, 3/5/2018



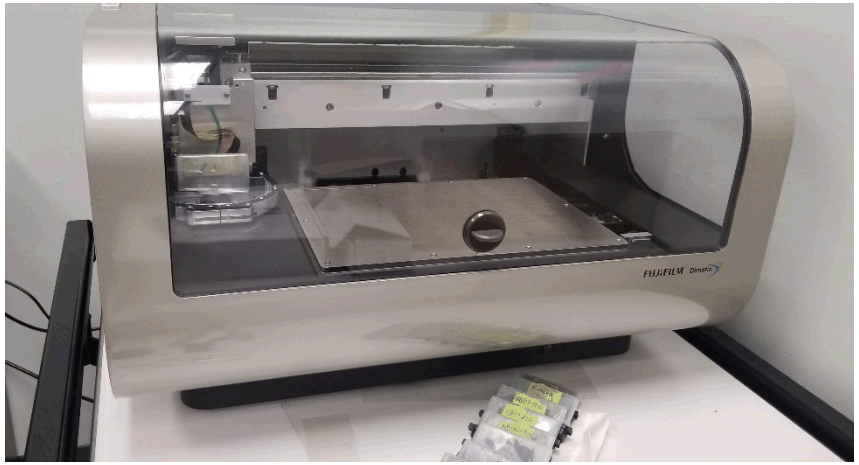




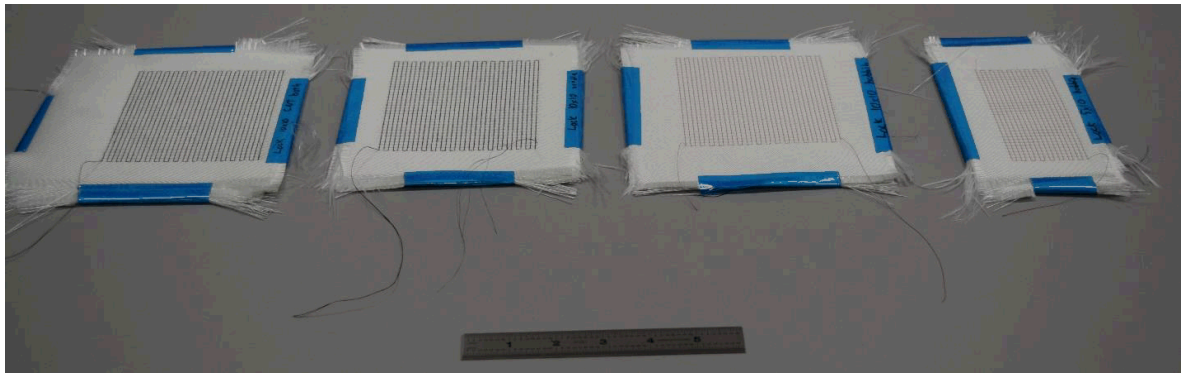
CNT sensor shows opposite response vs. strain. Data is also shifted by ~600 points (40 seconds) due to later start of DAQ

Future Directions

- Fujifilm Dimatix Material Printer procured and under testing for conductive ink and graphene printing.



- Phase III and Phase IIx SBIR under way to investigate stitched CNT sensor performance and characteristics.



Summary

- Multifunctional CNT and rGO sensors have been developed, printed on unique substrate geometry and flight tested.
- Nanomaterial sensors survived the flight environment and recorded data with a profile similar to the commercial strain gauge control.
- Temperature changes have a major effect on the sensor outputs. Temperature correction algorithms and techniques incorporating hopping conduction mechanism are being developed and applied for nanomaterial sensors.
- Continued research required for optimization of RGO and CNT sensors and multifunctional systems.
- University funded (NSTRF) research on *2D Materials for Energy Harvesting and Sensing* seeks to add capabilities for structural health monitoring or aerospace structures.