ASME QNDE 2023

Quantitative Nondestructive Evaluation

CONFERENCE JULY 24–27, 2023

ASME QNDE 2023 Quantitative Nondestructive Evaluation

MEASUREMENT SYSTEM ANALYSIS OF A NOVEL PHASE-BASED ULTRASONIC NDE TECHNIQUE FOR BOND STRENGTH MEASUREMENT

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ASME QNDE 2023 Quantitative Nondestructive Evaluation

Outline

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2. Problem Statement
3. Technical Background
4. Experimental Setup
5. Results and Discussion
6. Conclusion and Future Work

Introduction

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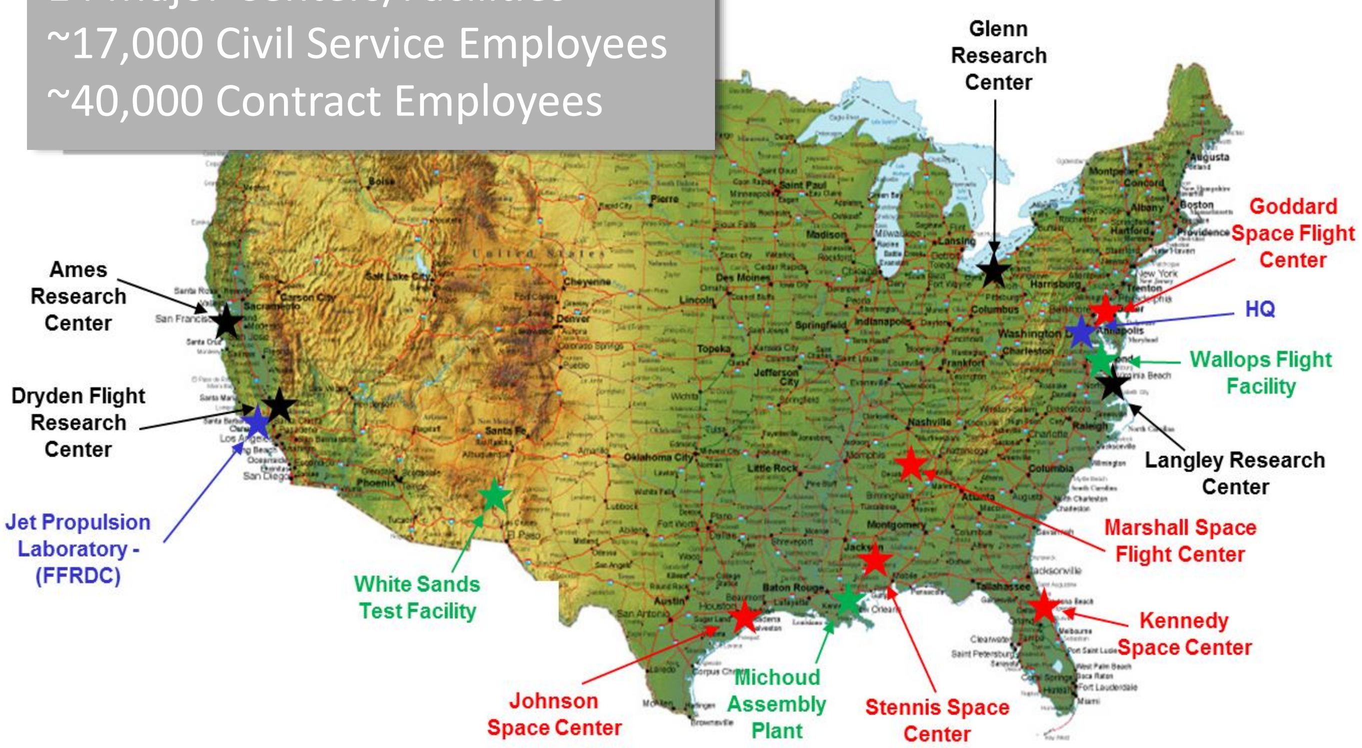
National Aeronautics & Space Administration (NASA)

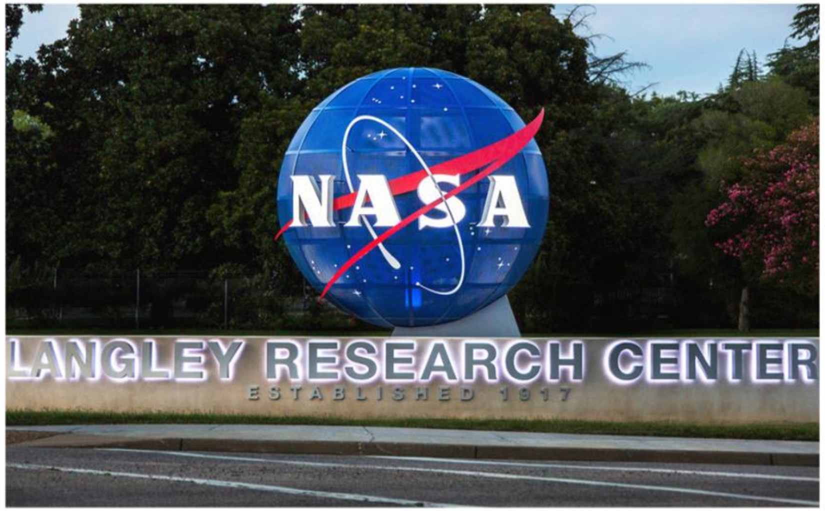
14 Major Centers/Facilities
~17,000 Civil Service Employees
~40,000 Contract Employees



NASA Langley is the oldest center, 106 years!

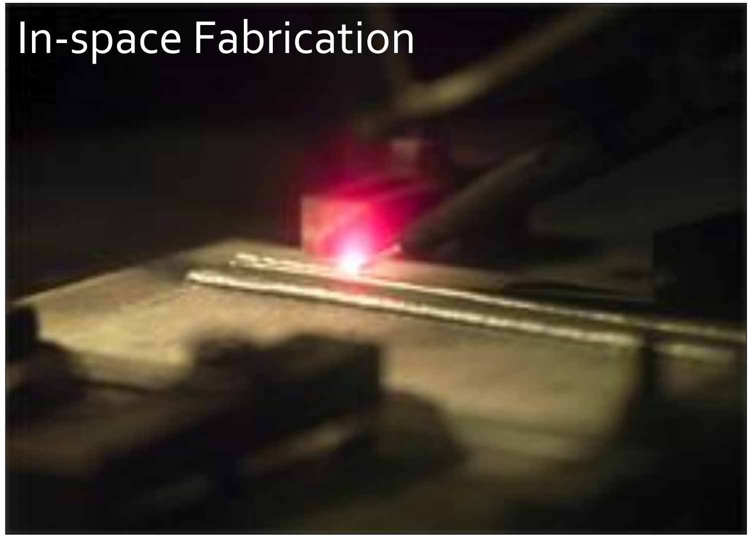
Centers & Facilities:

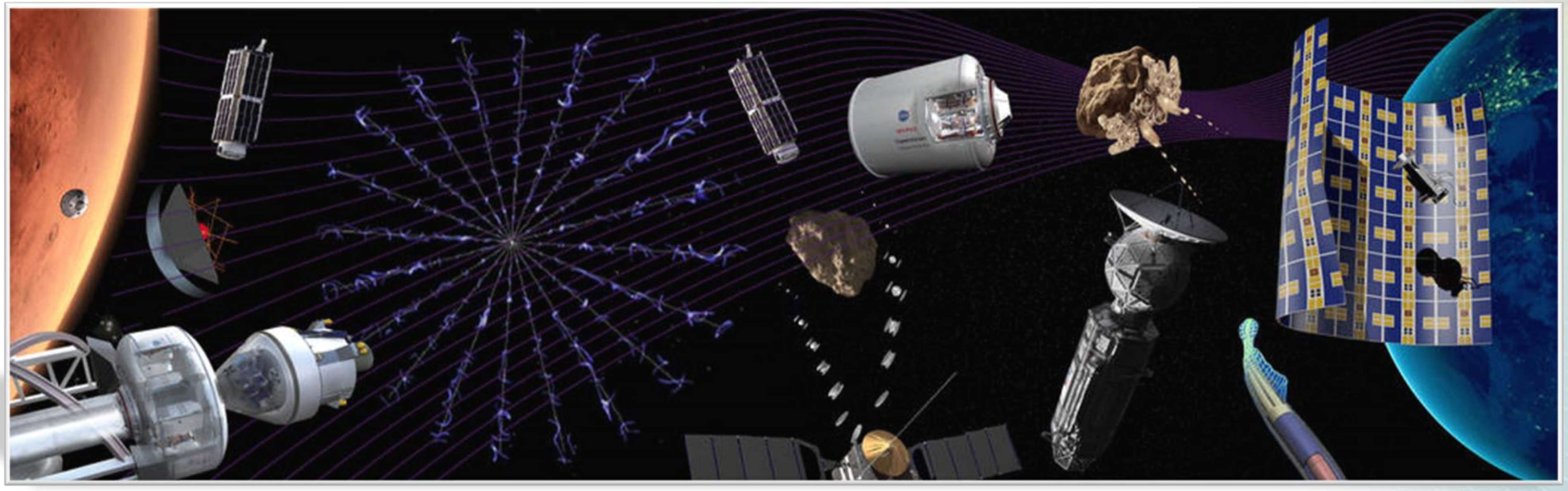
- Ames Research Center
- Armstrong Flight Research Center
- Glenn Research Center
- Goddard Space Flight Center
- Jet Propulsion Laboratory
- Johnson Space Center
- Kennedy Space Center
- Langley Research Center
- Marshall Space Flight Center
- Michoud Assembly Plant
- NASA Headquarters
- Stennis Space Center
- Wallops Flight Facility
- White Sands Test Facility



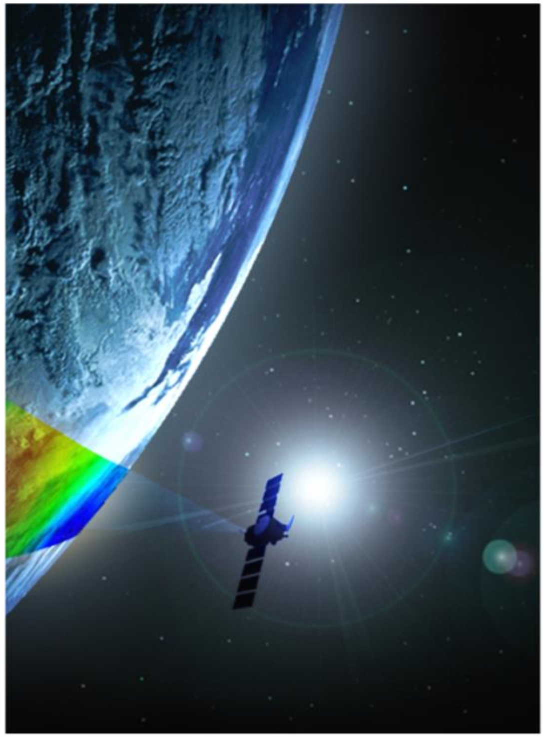
NASA Langley Research Center
National Resource for Aerospace R&D
Since 1917

Space Technology

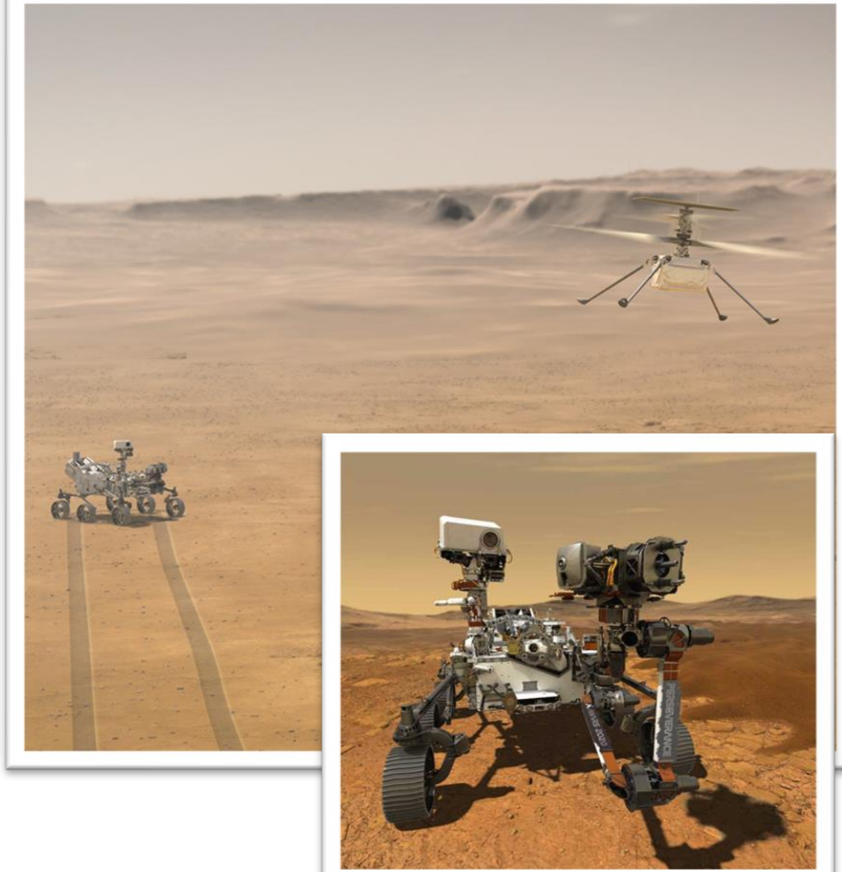




Science



Earth Sensing



Robotic Planetary Exploration
Perseverance: Landed on Mars February 2021

Solar System and Beyond

JWST: IR imaging. 21 ft mirror

Kepler Spacecraft: 2600+ exoplanets

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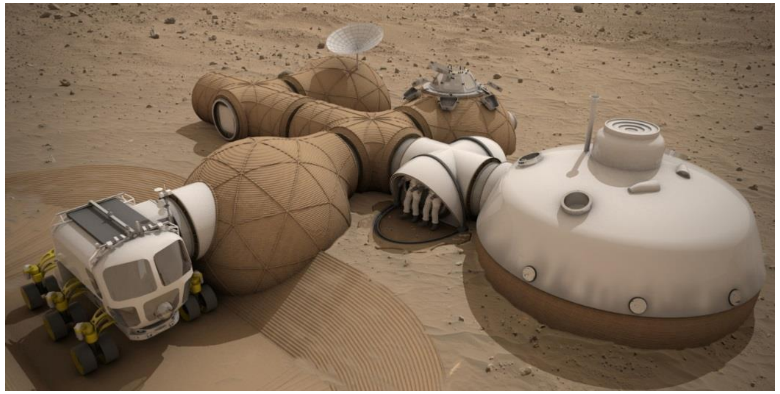
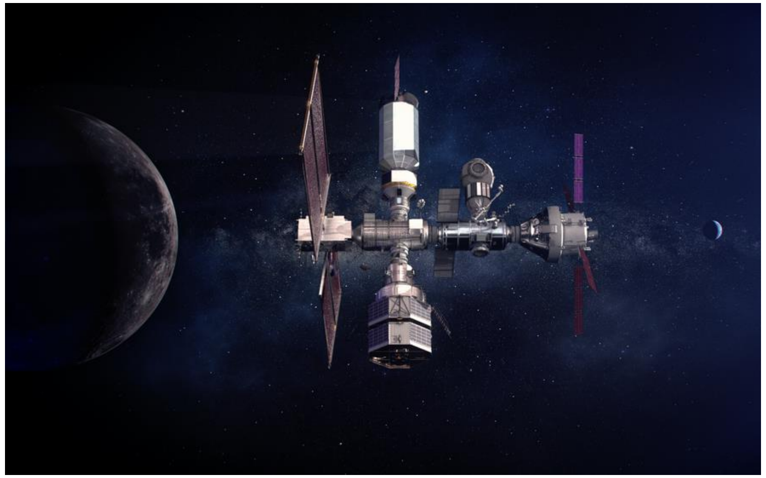
Human Exploration



Human Habitation for Moon and Mars



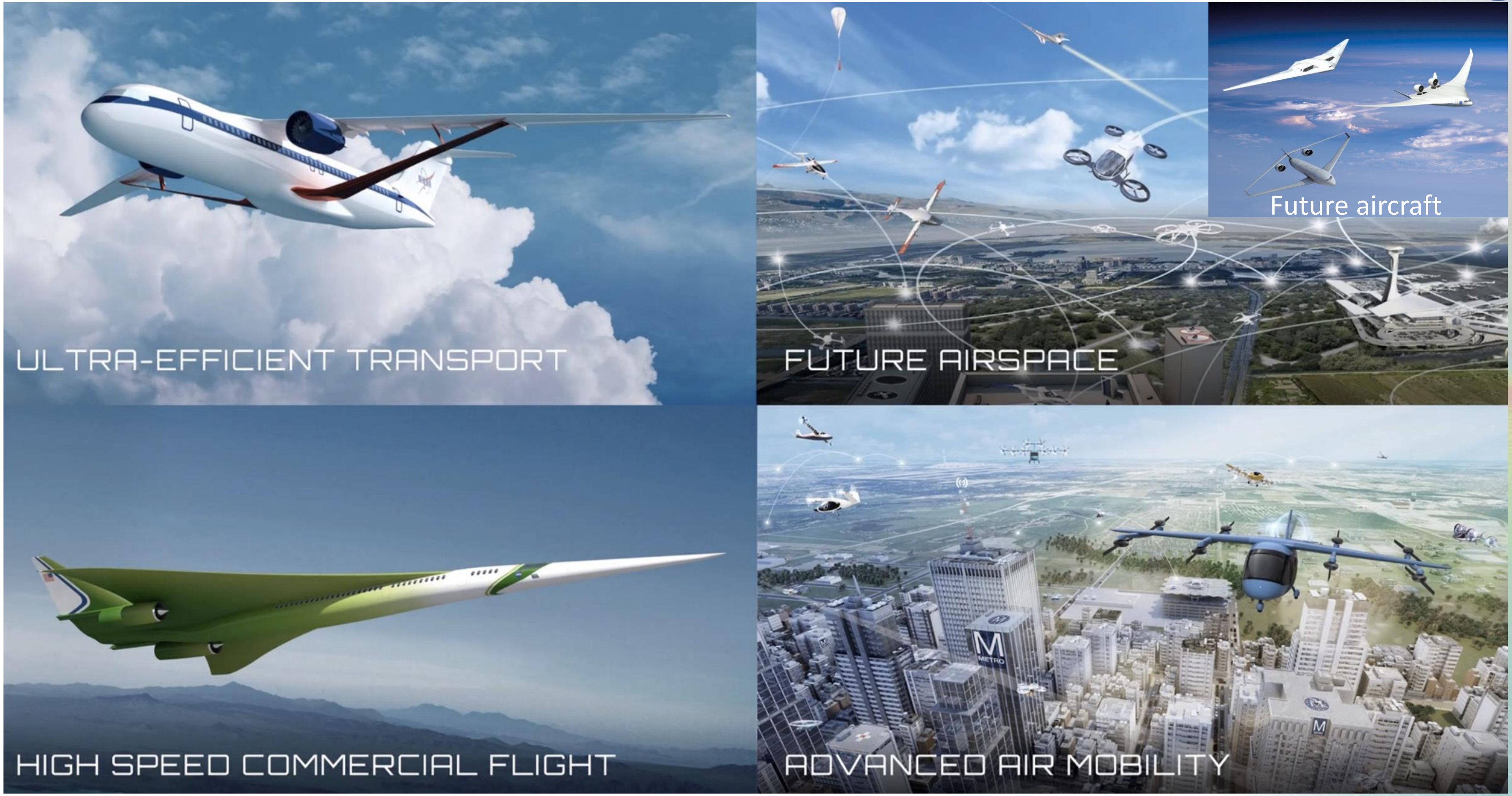
Lunar Gateway

Artemis:
Space Launch System (SLS)

Commercial Crew to ISS

International Space Station

Aeronautics



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Problem Statement

Bonded Composite Joints

- Usage expected to increase in next generation aircraft
  - Currently requires extensive use of structurally redundant fasteners
    - Slow to install -> hole drilling, fastener installation, inspection and sealing
    - Lost of envisioned manufacturing advantages of bonding
- Lightweight adhesively-bonded parts
  - Have shown some great benefits, including improvements in:
    - ✓ Mechanical properties, fuel efficiency, flight range and payload
    - ✓ Reduction in aircraft operation costs
  - More efficient than mechanical joints
    - ✓ Ability to distribute load over a much broader area


Future aircraft

Bonded Composite Joints

- Lightweight adhesively-bonded parts
  - **<u>Problem</u>**: Development, qualification and mainstream adoption
    - Impeded by the lack of reliable and quantitative NDE method or technique for quality assurance
    - Current commercial NDE typically detect gross bonding defects (e.g., delaminations, voids, major porosity, etc.)
      - Albeit, in a more qualitative (Pass/Fail) manner
      - These techniques fail to detect weak or kissing bonds
    - Bond strength is currently ensured by process control and semi-destructive testing
  - **<u>Proposed Solution:</u>** A novel phase-based ultrasonic technique
    - ✓ Developed at NASA Langley Research Center (LaRC)
    - ✓ Based on a constant frequency phase-locked loop (CFPLL) technology
  - **<u>Objective:</u>** Perform a Measurement System Analysis (MSA) study to evaluate the novel phase-based ultrasonic system for bond quality assessment
    - ✓ Novel system's precision, repeatability and reproducibility (R&R)
      - Analysis of Variance (ANOVA) method
      - Components of variation in the measurement process

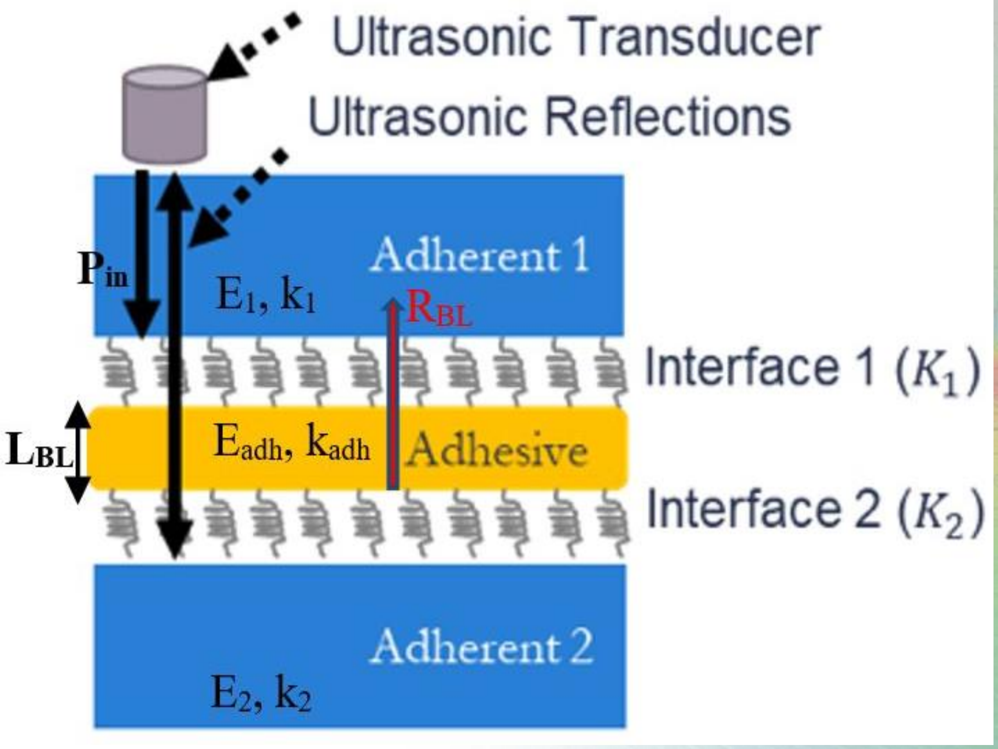
Technical Background

Physics-Based Model of Adhesion

- Theory of Ultrasonic Interaction with Imperfectly Bonded Interfaces
  - Adhesion is modeled by a massless spring network of mechanical connections between the adhesive and adherents
    - ✓ Tri-layer adhesively bonded joint illustrated
  - The interfacial adhesive bond quality is represented by the interfacial stiffness ($K_1=K_2=K$)
    - ✓ Defined as the stiffness per unit area
  - Tattersal's simplified model* for a given normal incidence

$$R = \frac{Z_1 - Z_2 + i\omega \frac{Z_1 Z_2}{K}}{Z_1 + Z_2 + i\omega \frac{Z_1 Z_2}{K}}$$

- ✓ Perfect adhesion: $K \to \infty, R \to 0$
- ✓ Complete disbond: $K \to 0, R \to 1$



*Tattersall, H. G. *The Ultrasonic Pulse-Echo Technique as Applied to Adhesion Testing.* Journal of Physics D: Applied Physics, **1973,** 6, 819-832

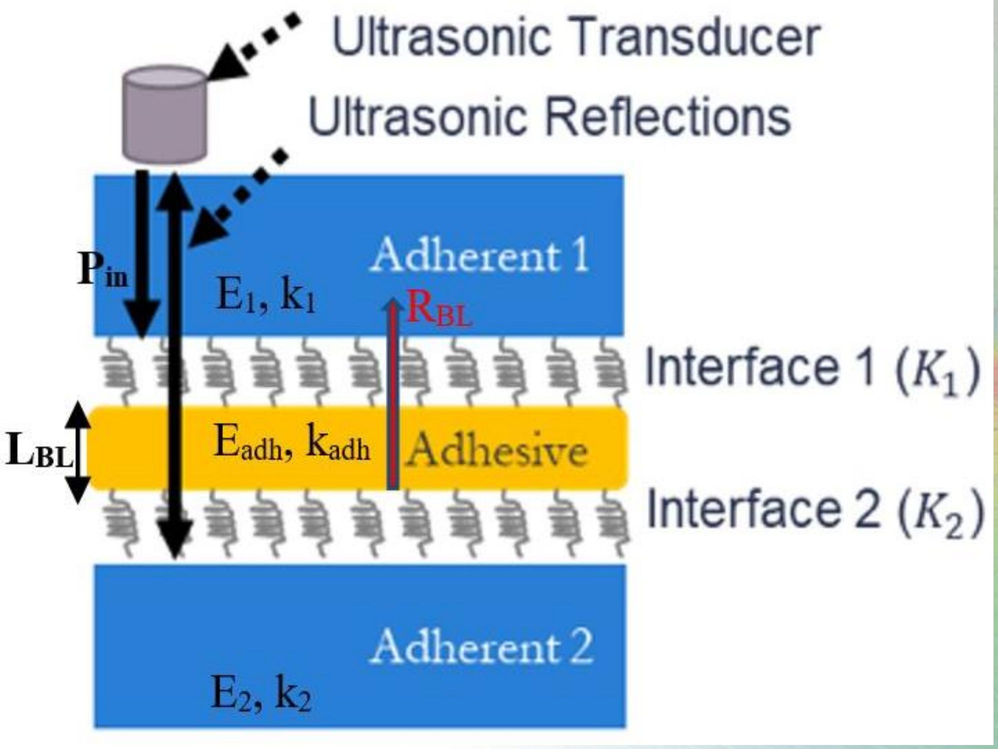
Physics-Based Model of Adhesion

- Consideration of adhesive properties
  - More thorough analysis gives complex reflection coefficient as*:

$$R_{BL} = \frac{C_N \cos(k_{adh}L_{BL}) + iS_N \sin(k_{adh}L_{BL})}{C_D \cos(k_{adh}L_{BL}) + iS_D \sin(k_{adh}L_{BL})}$$

$$\begin{cases} C_N = \frac{G_1^2}{K} \\ C_D = 2G_1G_{adh}\left(1+\frac{G_1}{K}\right) \\ S_N = G_1^2 - G_{adh}^2 + \left(\frac{G_1G_{adh}}{K}\right)^2 \\ S_D = G_1^2 + G_{adh}^2 + \frac{G_1G_{adh}^2}{K}\left(2+\frac{G_1}{K}\right) \end{cases}$$

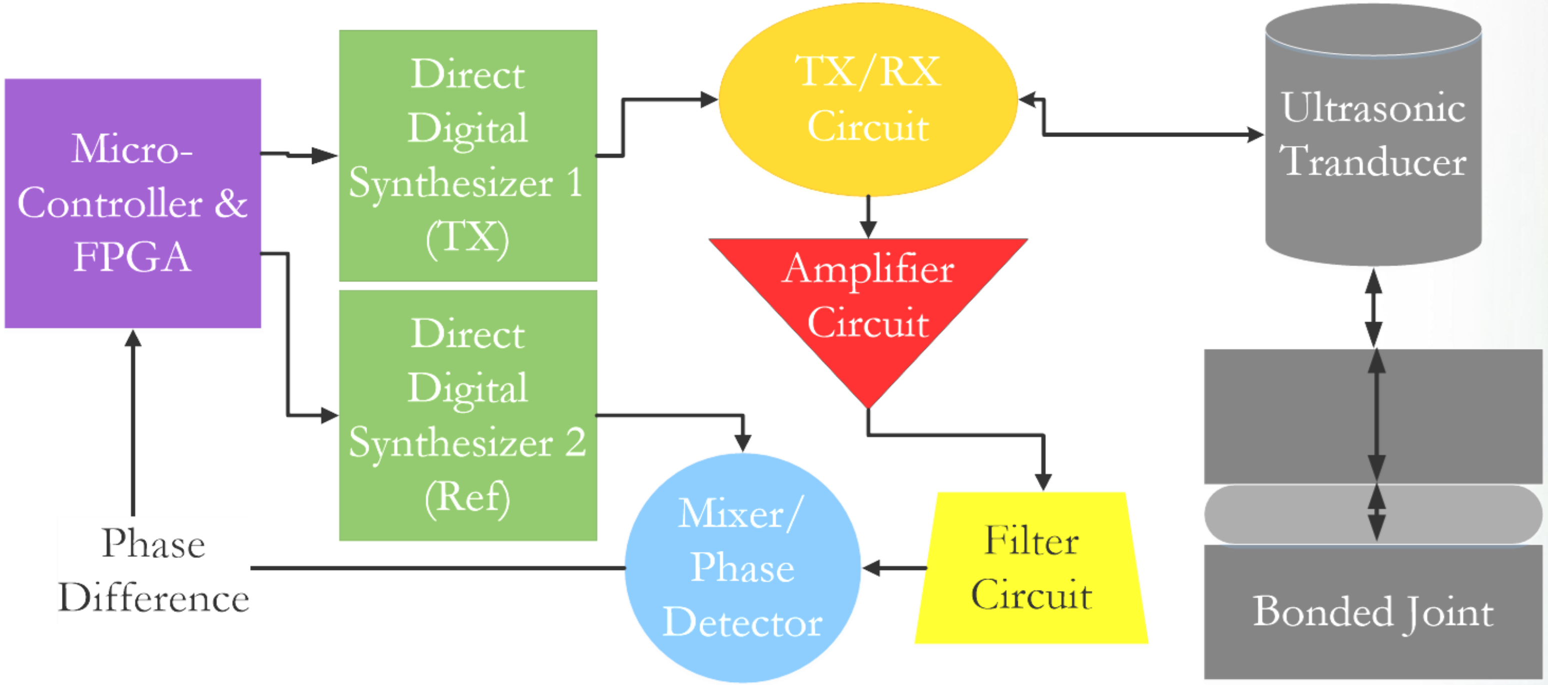
where $G_1 = E_1k_1$, $G_{adh} = E_{adh}k_{adh}$ and $i = \sqrt{-1}$



- *The unknown adhesive bonding properties can be extracted by fitting the measured phase response of the bondline to the theoretical R_{BL}*

*Haldren, H. A. *Nondestructive Evaluation of Adhesive Bonds by a Novel Ultrasonic Phase Measurement Method*, A Ph.D. Dissertation presented to the Faculty at the School of Engineering and Applied Science, University of Virginia, **May 2020**

Constant Frequency Phase-locked Loop*



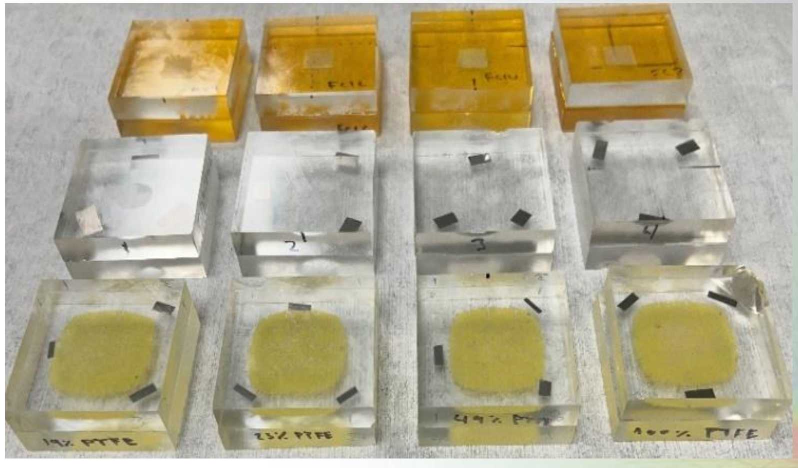
- Comparing the received ultrasonic waveform reflected off bonded interface
  - To a reference waveform of the same frequency
- Comparing the two signals allows measurement of the phase shift in the bonded joint
  - With high resolution and low uncertainty
- When repeated over a band of frequencies around the anti-resonant frequency
  - Results to a phase spectral response
- Quality of the bond
  - Could be inferred from the resulting phase spectral response

*Yost, W. T.; Cantrell, J. H.; Kushnick, P. W. *Fundamental Aspects of Pulse Phase-Locked Loop Technology-based Methods for Measurement of Ultrasonic Velocity*. Journal of the Acoustical Society of America **1992**, 91(3), 1456-1468

Experimental Setup

Test Samples for the Gage R&R Study

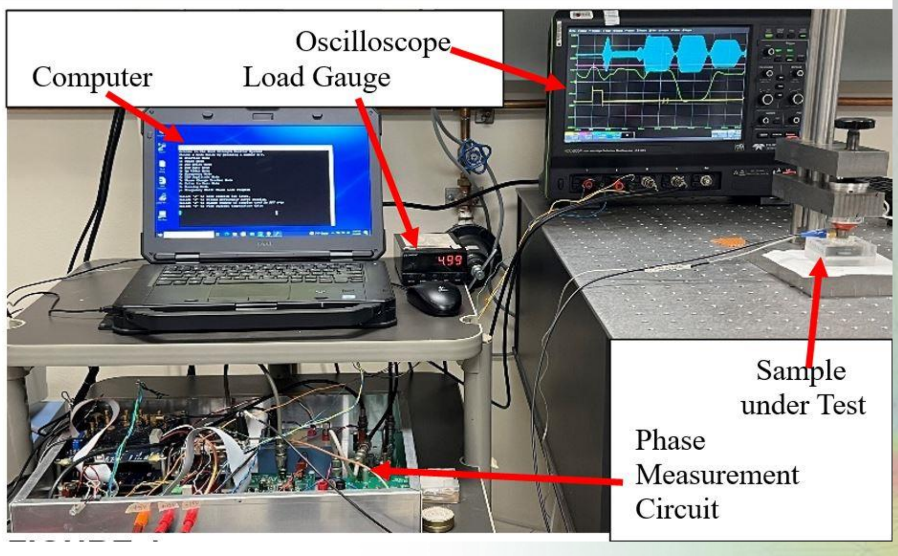
- Simplistic borosilicate (BS) adhesively bonded glass specimens:
  - Used for proof of concept
    - ✓ Can this novel phase-based NDE technique assess bond strength?
  - Optically transparent, smooth surfaces and no microstructure
    - ✓ Helps to eliminate any confounding effect in experimentations
    - ✓ Creates a path towards phase-based ultrasonic NDE of:
      - Metallic bonded joints,
        - Grain noise becomes relevant, and
      - Ultimately, bonded composite joint,
        - Multi-layer laminate and fiber interactions present more complexity
- Gage Repeatability and Reproducibility (Gage R&R)
  - How precise is the novel measurement device for bond strength?
  - Performed on these bonded glass specimens
    - ✓ Produced under various degrading conditions, including:
      - Epoxy adhesive with varying % of Polytetrafluoroethylene (PTFE) coverage area
      - FM209-IU adhesive with varying thermal conditions
      - UV-cured NOA60 adhesive at varying UV exposure times
    - ✓ <u>Coupons</u>: *5.08 cm* x *5.08 cm* and *1.10 cm* thick. <u>Bondline</u>: ~100 µm thick

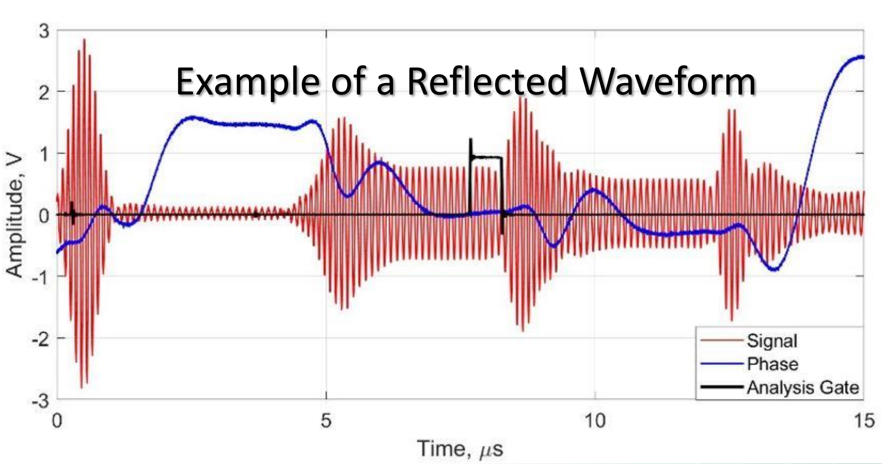


Sample ID	Description of Adhesive Condition
Cont19	Epoxy adhesive with 19% PTFE coverage
Cont23	Epoxy adhesive with 23% PTFE coverage
Cont49	Epoxy adhesive with 49% PTFE coverage
Cont100	Epoxy adhesive with 100% PTFE coverage
FC1	FM209-1U fully cured at 250^{0}F
FC1C	FM209-1U fully cured at 250^{0}F Contaminated with 20% PTFE coverage
FC1U	FM209-1U under cured adhesive
FC2	FM209-1U fully cured at 350^{0}F
UV1	NOA60 adhesive with 60 mins UV exposure
UV2	NOA60 adhesive with 180 mins UV exposure
UV3	NOA60 adhesive exposed for 30 mins (aged)
UV4	NOA60 adhesive exposed for 60 mins (aged)

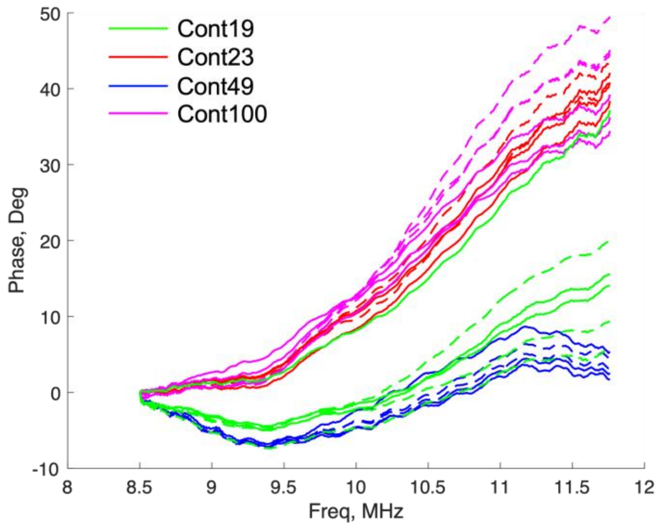
Data Collection for Gage R&R Study

- Laboratory setup of the ultrasonic phase-based instrument
  - Highly-damped 10 MHz contact transducer of 0.25” diameter
    - Placed in the center of each sample
    - Held in place using a screw clamp at constant load of ~5 lbs
    - Excited with tone-burst
      - Swept over frequency range from 8.5 MHz – 11.75 MHz
      - 10 KHz step size
  - Ultrasonic phase measurements from each of the test samples
    - Obtained in pulse-echo mode
    - By two separate operators
      - 3 times each in a randomized manner
      - Taking out test sample from the fixture between measurements
      - Using best practices to reposition transducer for new measurement
  - Computer was used to control the phase measurement circuit
    - Taking phase measurements of the 1st reflected signal
      - From the adhesive surface at each frequency
      - Recording the measured phase
    - Analysis region selected where the measured phase was constant
      - Stable as possible over the entire frequency range

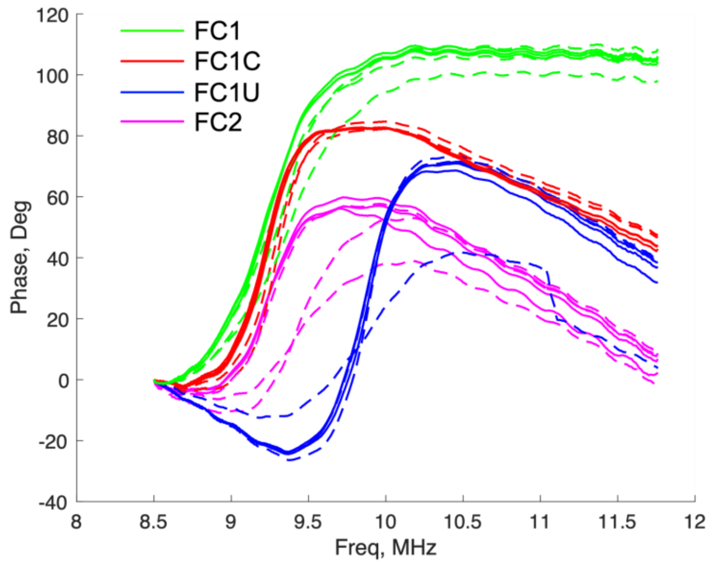




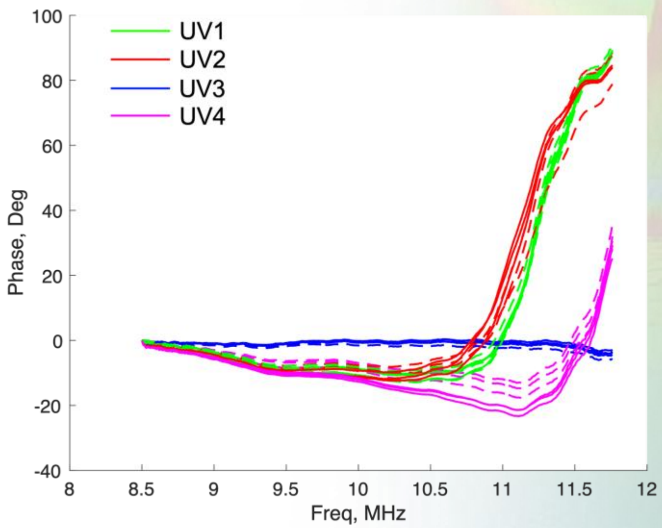
Bondline Phase Responses of Each Group



(a) PTFE Contaminated

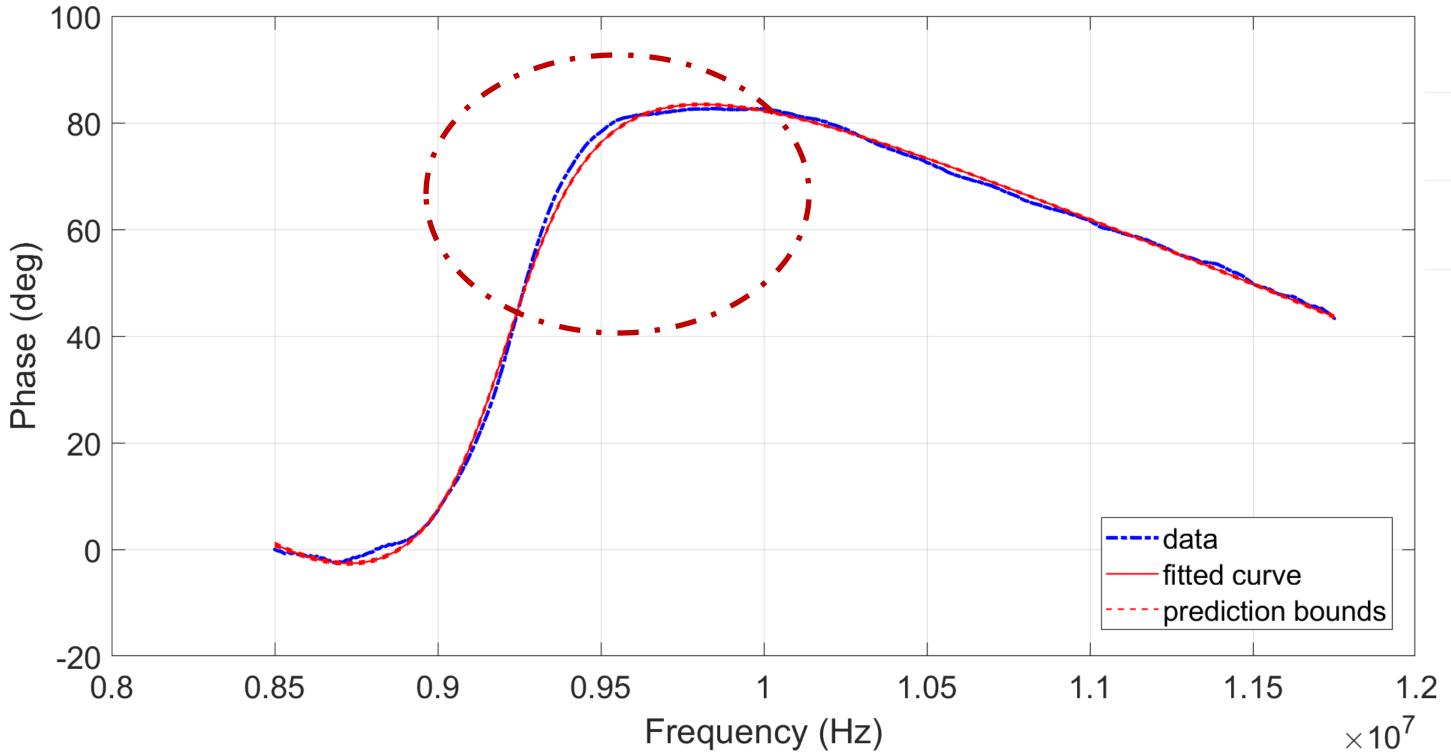


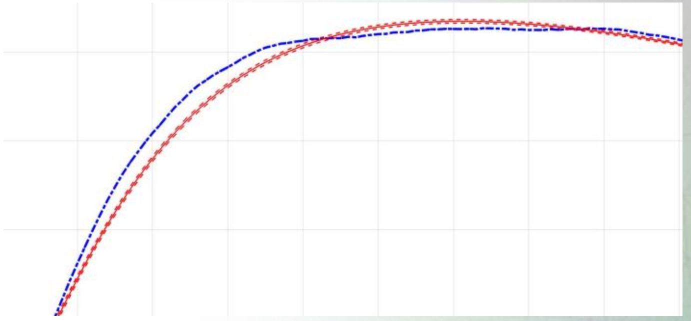
(b) FM209-IU



(c) NOA60 UV-Cured

Example of a Fitted Phase Data

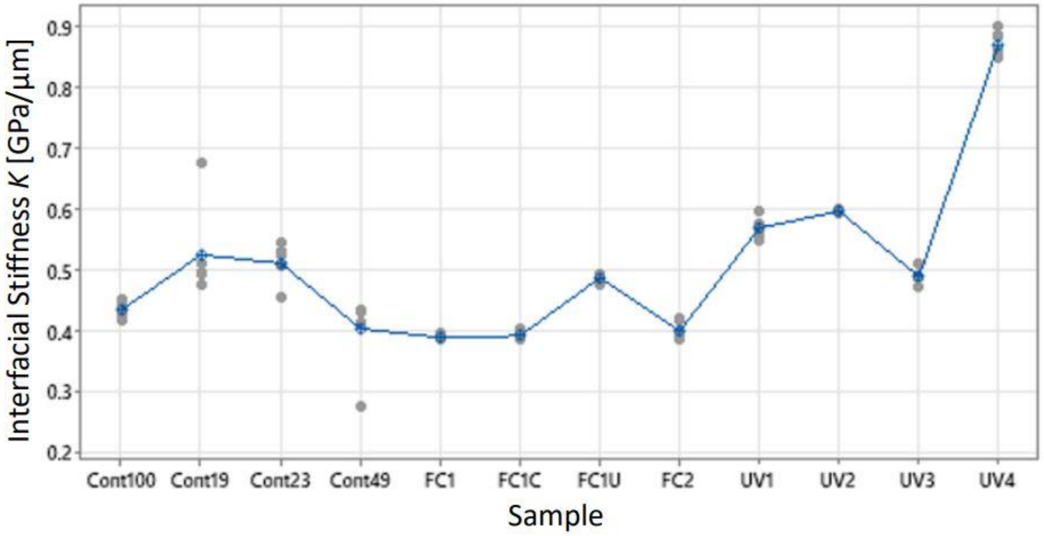




- ❑ Extracted Interfacial Stiffness for Gage R&R study
  - ➢ From phase change data
    - ✓ Minimizing the difference between this measured phase change and the spring model
    - ✓ Using a nonlinear least-squares approach in Matlab®

Results and Discussion

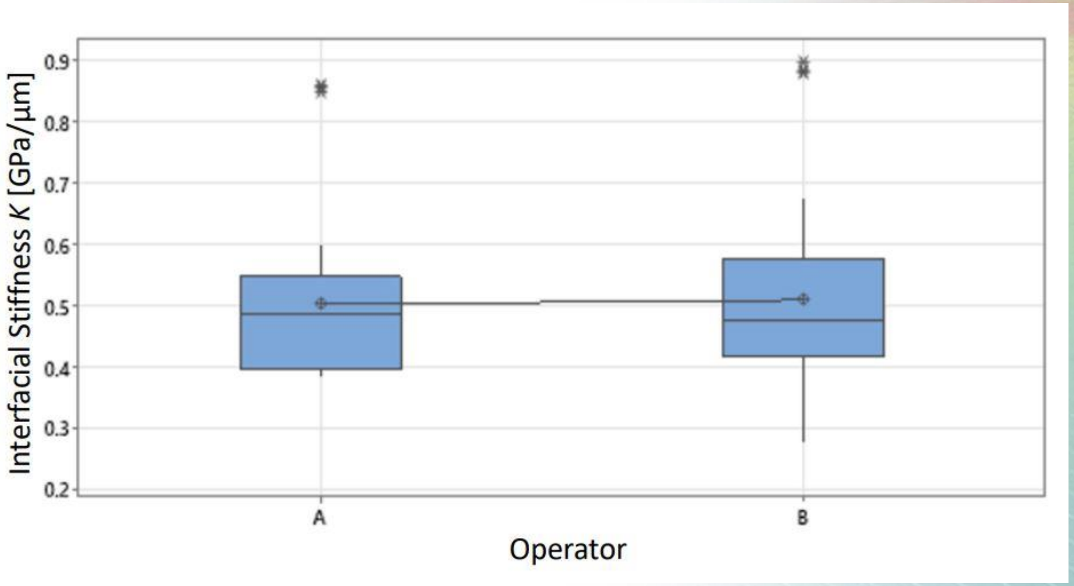
Extracted Values of Interfacial Stiffness *K*



- ❑ PTFE contaminated samples vary noticeably
  - ➢ Assignable cause variation
    - ✓ Defects in the epoxy adhesive layer →

- ❑ Other 2 groups of parts
  - ➢ Measured relatively consistently
- ❑ Measured averages of all parts vary noticeably
  - ➢ Desirable as samples should represent wide range of values

- ❑ Measurement spread
  - ➢ Approximately the same for each operator
    - ✓ Indicating both operators are measuring parts similarly
- ❑ Outliers
  - ➢ Measured similarly by each operator



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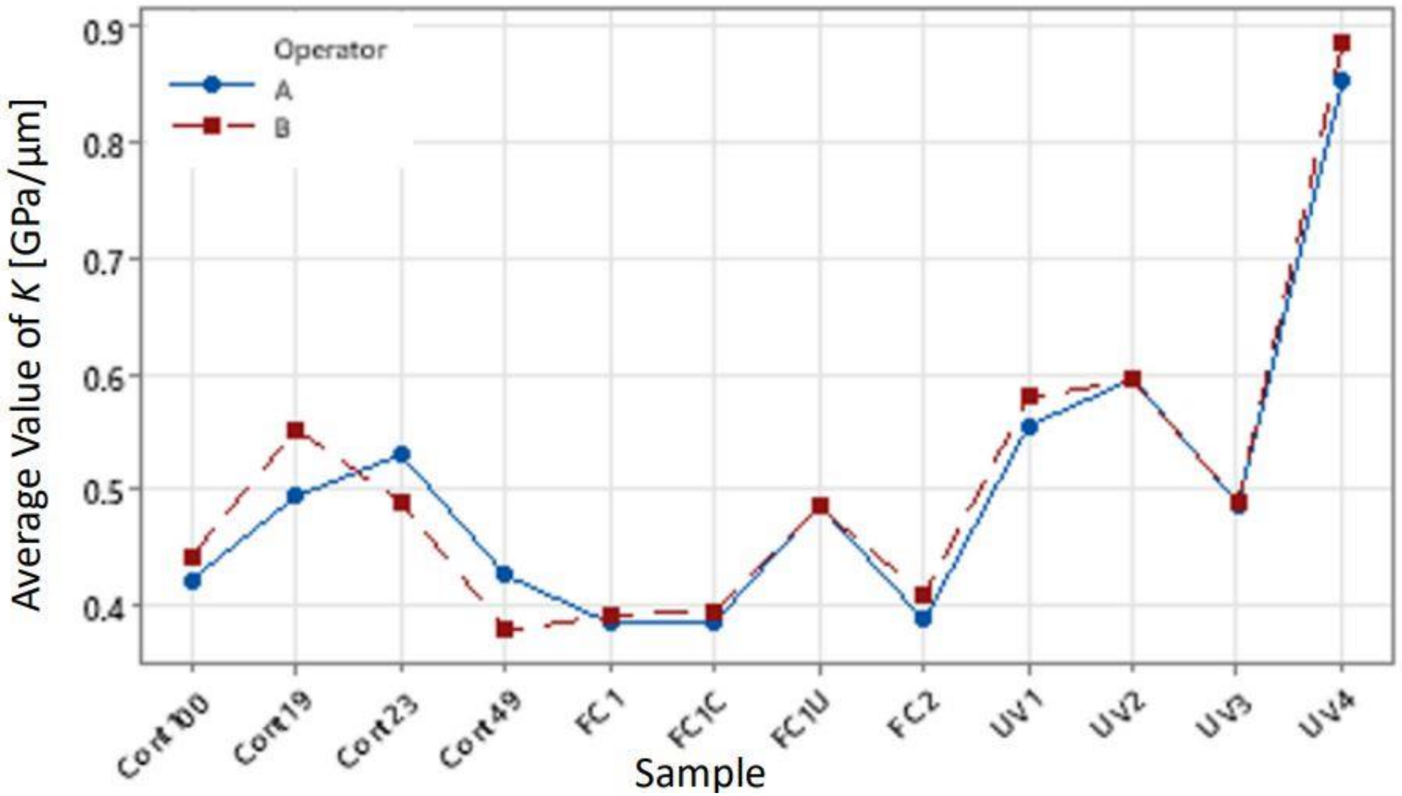
Extracted Values of Interfacial Stiffness *K*



- ❑ Sample-Operator Interaction plot
  - ➢ Measurement inconsistency of the PTFE contaminated samples observed
    - ✓ PTFE contaminated sample with defects →
  - ➢ Lines follow very closely for FM209-1U and NOA60 UV-cured samples

Contribution of Each Source of Variation

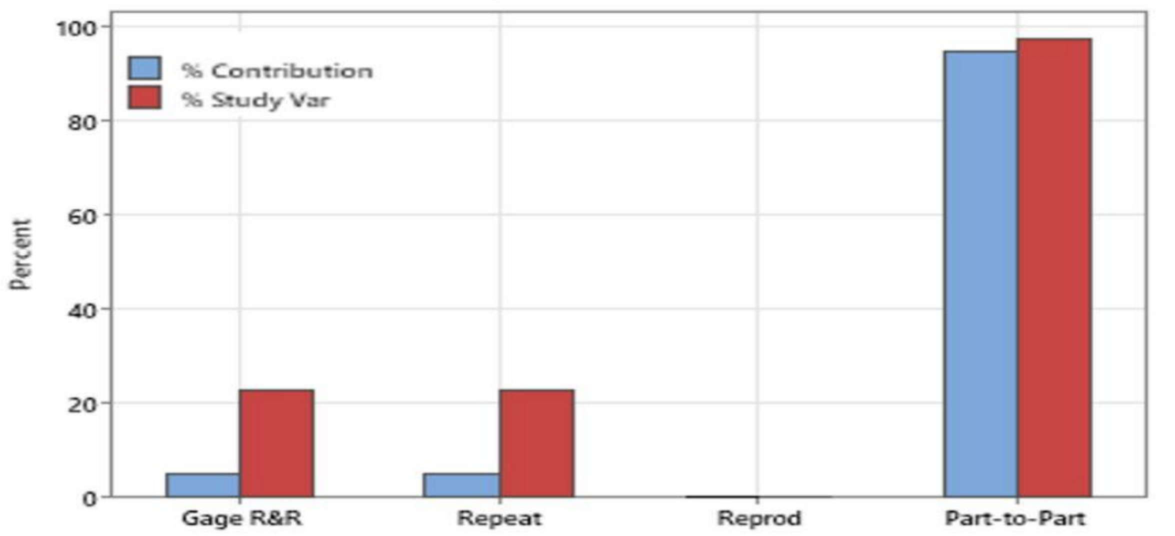
VARIANCE COMPONENTS

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0010034	5.27
Repeatability	0.0010034	5.27
Reproducibility	0.0000000	0.00
Operator	0.0000000	0.00
Part-To-Part	0.0180304	94.73
Total Variation	**0.0190338**	**100.00**

STUDY VARIATION

Source	Study Var (6 x SD)	%Study Var (%SV)
Total Gage R&R	0.190063	22.96
Repeatability	0.190063	22.96
Reproducibility	0.000000	0.00
Operator	0.000000	0.00
Part-To-Part	0.805663	97.33
Total Variation	**0.827778**	**100.00**

- Total variation
  - 94.73% comes from sample-to-sample variability
  - 5.27% is from measurement instrument (Total Gage R&R)
    - ✓ The Total Gage R&R is entirely from repeatability error
    - ✓ Reproducibility error ~0% (to the number of decimal places)
      - Different operator can precisely and similarly
        - Measure same samples with same instrument
    - ✓ Acceptable Gage, as per Industry guideline of < 10%



Conclusion and Future Work

Conclusion and Future Work

- Measurement System Analysis (MSA) conducted
  - To assess the quality of the novel ultrasonic phase-based bond strength instrument
  - Specifically, the instrument's precision (repeatability and reproducibility) has been evaluated
    - ✓ Through a Gage R&R study using the ANOVA (Analysis of Variance) method
  - Study results show this new device can precisely measure interfacial stiffness
    - ✓ Adhesively bonded BS specimens
    - ✓ Most of the measurement variation coming from the samples instead of the instrument
      - Potentially due to bondline thickness variation across the samples
- Ultimate goal is to measure bond strength of composite bonded samples
  - This study on comparatively simplistic BS specimens provide roadmap for further development
    - ✓ Laboratory-based instrument → field instrument
- Reproducibility error ~0% (for the level of precision reported)
  - Use of such devices could be independent of the operator
    - ✓ Useful as an in-service equipment to measure bond quality for aerospace parts in use
- **Future Work**: Accuracy (bias, linearity and stability) study
  - To get a full picture of the measurement variation of this novel device

Acknowledgments

- NASA Transformation Tools and Technologies (TTT) project
  - Aeronautics Research Mission Directorate
    - ✓ Fully supporting this work
- TTT Composite Bonded Joint NDE Team members
  - Matthew Webster, Peter Spaeth and Joseph Zalameda
- Nondestructive Evaluation Sciences Branch at NASA Langley Research Center
  - Dan Perey
    - ✓ Design, build and support of the Constant Frequency Phase-lock Loop circuit
- Minitab (version 21.2), license owned and hosted by NASA
  - Used for planning and analyzing results for the Gage R&R study

Questions