Large-Standoff Large-Area Thermography
LASLAT

Developed under SBIR NAVAIR N092-097

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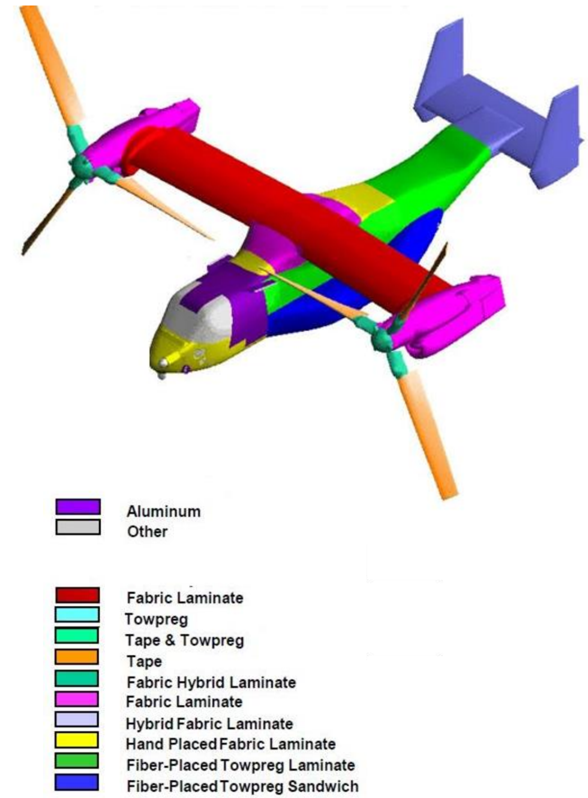
Challenge: NDI of Large Scale Composite Structures

- Aggressive Non-Destructive Inspection (NDI) is integral to maintaining warfighter readiness
  - Effective NDI detects the earliest indication of defects
  - Components can be repaired or replaced before the structural integrity or performance of the aircraft is compromised
- NDI of composite aircraft presents challenges to current NDI methodologies
  - No visual indications of damage
  - Large areas must be inspected

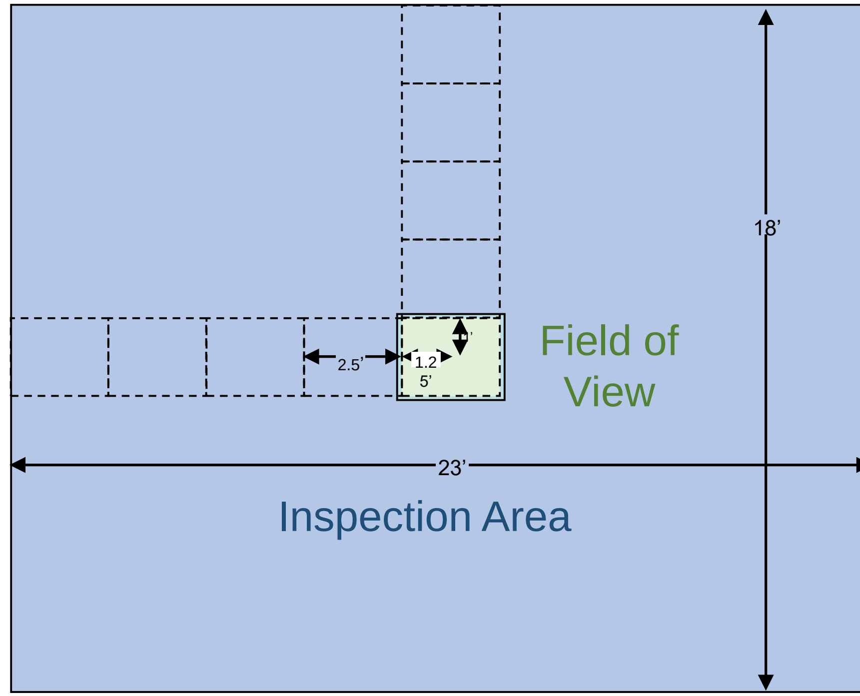


More than 43% of the V-22 airframe is built with composite materials

Conventional Approaches to Large Area NDI

Point coverage (UT)

1 sq. ft. coverage (Flash Thermography)



Move sensor over inspection field using

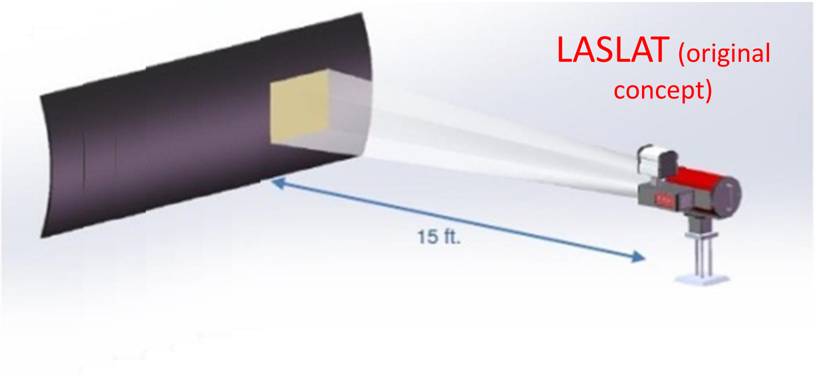
- Manually
- Fixed gantry
- Robotic system
- Creeper/ scanner

Challenge: NDI of Large Scale Composite Structures

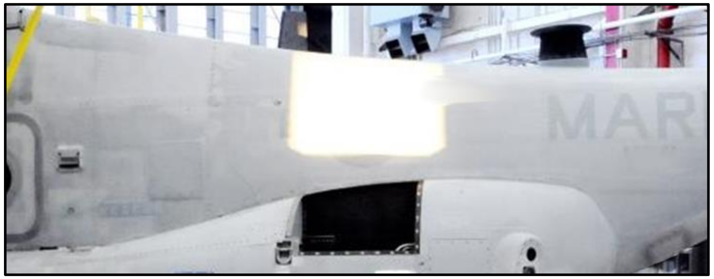
A more effective NDI solution should **address the complexities of composite aircraft inspection**, and **perform fast, 100% area inspection of large aircraft structures**.

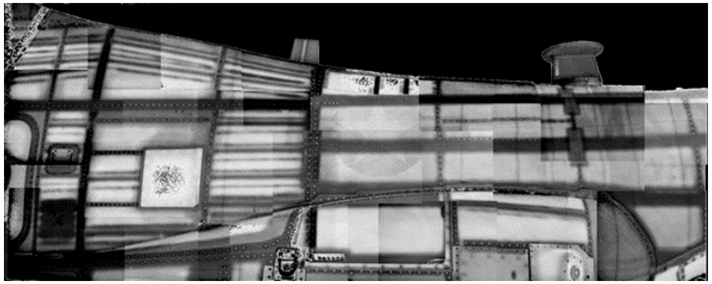
Objectives

- Minimize inspection turnaround time
- No gantry / robot or fixed installation required
- Easily adaptable for inspection of multiple platforms
- Simplify interpretation / analysis
- Operate in open hangar

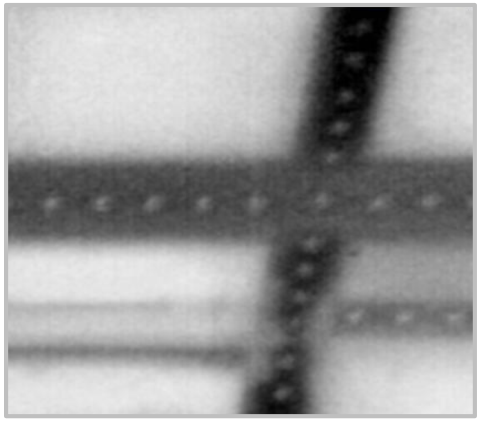


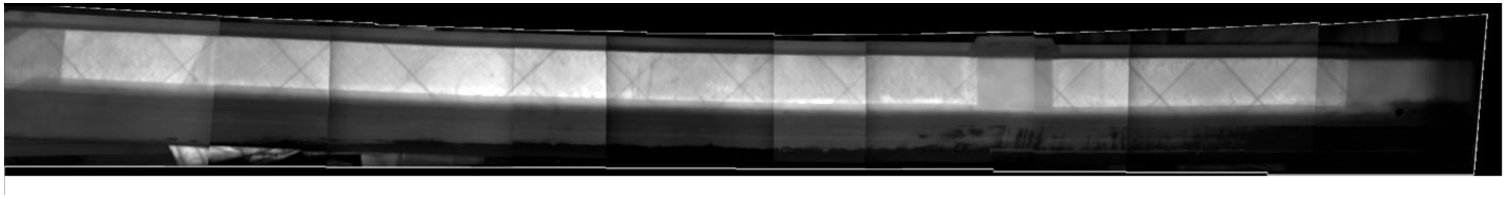
Large Standoff Large Scale Thermography (LASLAT)





NAVAIR SBIR
N092-097, FRC-E

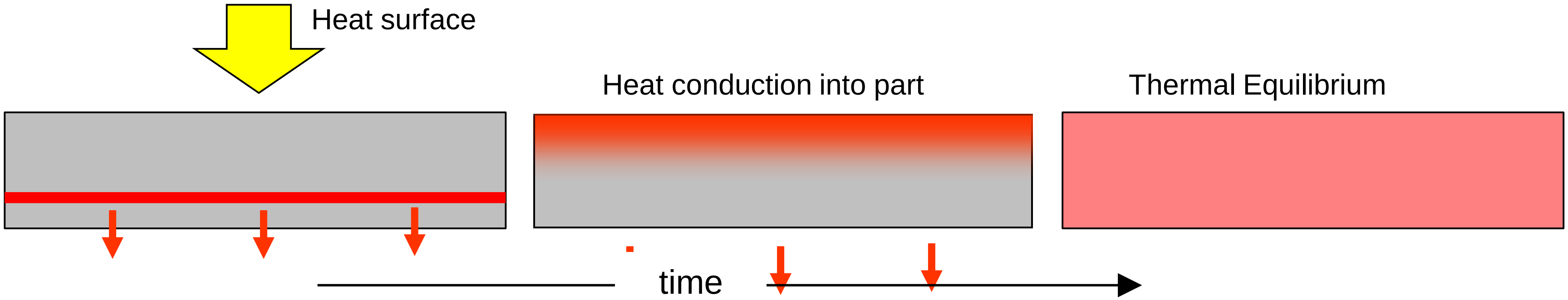




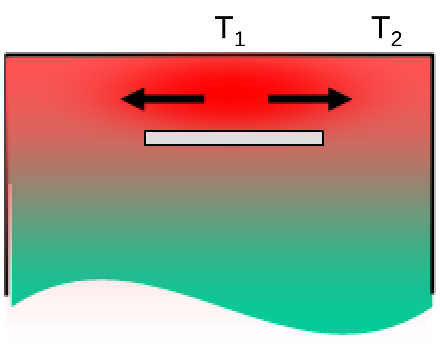
- Winner, 2016 DOD Maintenance Innovation Challenge
- Winner, 2017 Commercial Technologies for Maintenance Applications (CTMA) Technology Competition

Active Thermography Basics

- When we heat the surface of a sample, it cools in a predictable way.



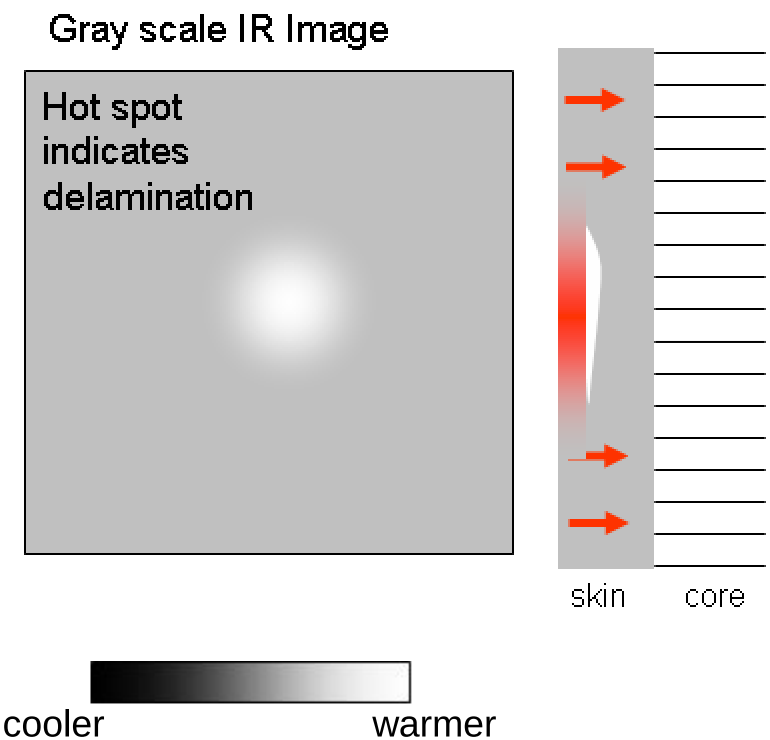
- Deviations from predicted surface cooling behavior indicate the presence of a subsurface feature.

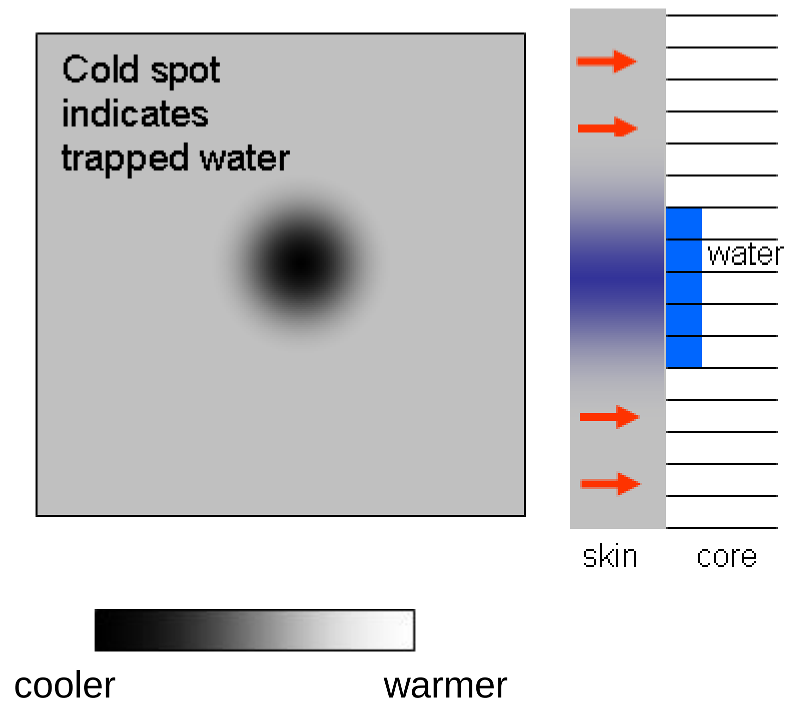


$T_1 > T_2$

IR Image

Typical Image Results





Delaminations <u>obstruct</u> the flow of heat and cause the surface to appear warmer.

Trapped water <u>absorbs</u> incident heat and causes the surface to appear cooler.

Large Scale Thermographic NDI

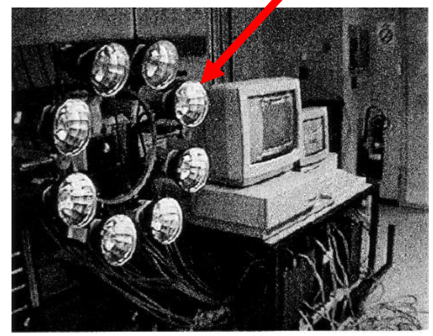
- A big part of the initial appeal of thermography
- Numerous attempts to implement
- Limited success

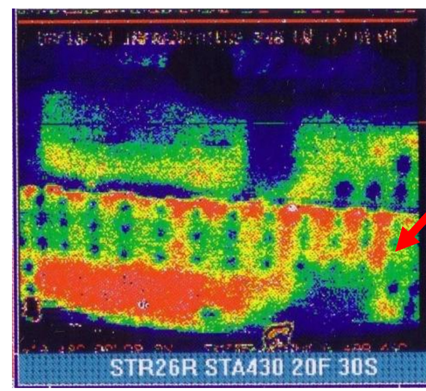
Large Scale Thermography: ~1992

Lap seam painted black

50 kJ energy (enough to blow out hanger circuits)

2 operators to perform inspection (more to process and analyze)

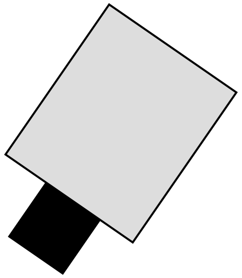




Single image result
- Inconclusive
- Post processed

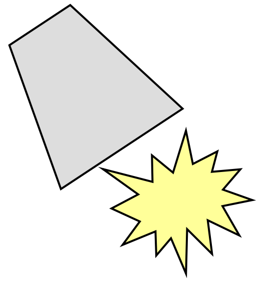
Field test at FAA-AANC Validation Center

Implementing Thermography



IR camera

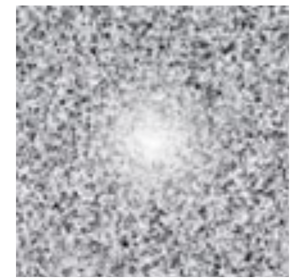
Cooled / uncooled
Sensitivity
Resolution
Speed
Cost
Size / weight



Excitation

Optical
Convective
Direct contact
EM induction
Acoustic
Solar

Pulse, step, scan…

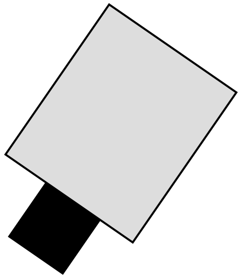


Processing

Direct viewing
Image processing
Signal processing

Thermography systems combine excitation, camera and image processing / viewing to match application requirements.

Implementing Thermography



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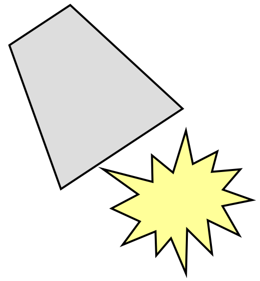

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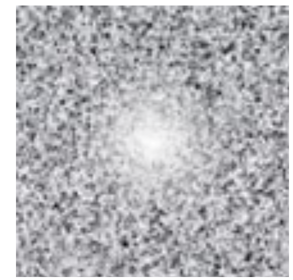

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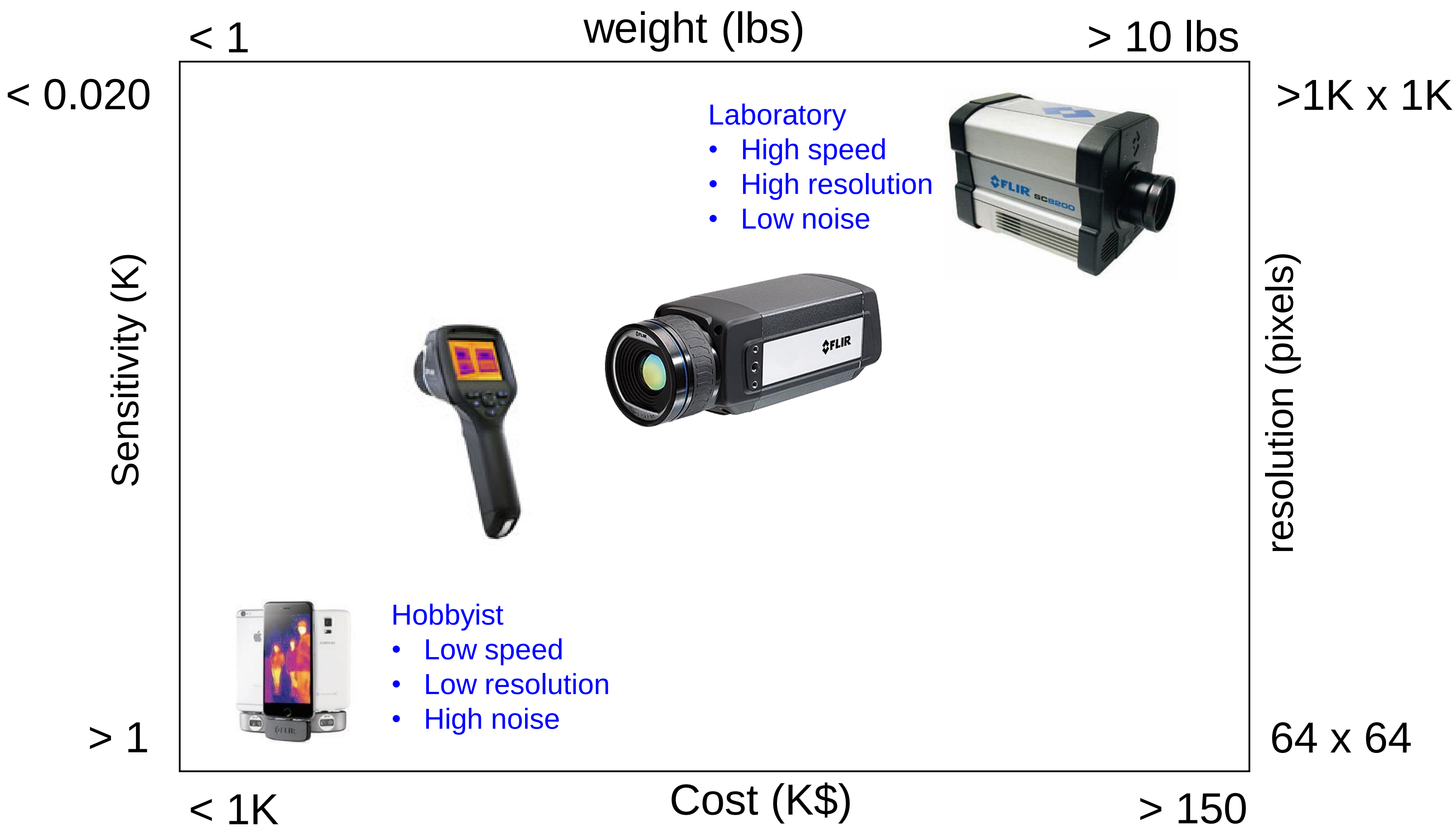
IR Camera: 1986

- LN2 cooling
- $65K (1986 USD)
- Single detector
  - Bi-directional mirror scan
- 8-bit analog output @ 30 Hz (pseudo)
  - Actual frame rate ~ 8 Hz
- Sensitivity: ~ 0.100 K
- Resolution: Ambiguous
- Analog frame grabber
  - No direct digital data transfer
  - Bandwidth limited – continuous data not available
- Tradeoff between dynamic range and sensitivity
  - Many shots saturated, unusable
- PC ~ 16-33 MHz

Inframetrics IR-600
U.S. Army TACOM

Modern IR Cameras



Field of View vs. Min Detectable Flaw Size

Q: What is the largest target I can image?

Field of View vs. Min Detectable Flaw Size

~~Q: What is the largest target I can image?~~

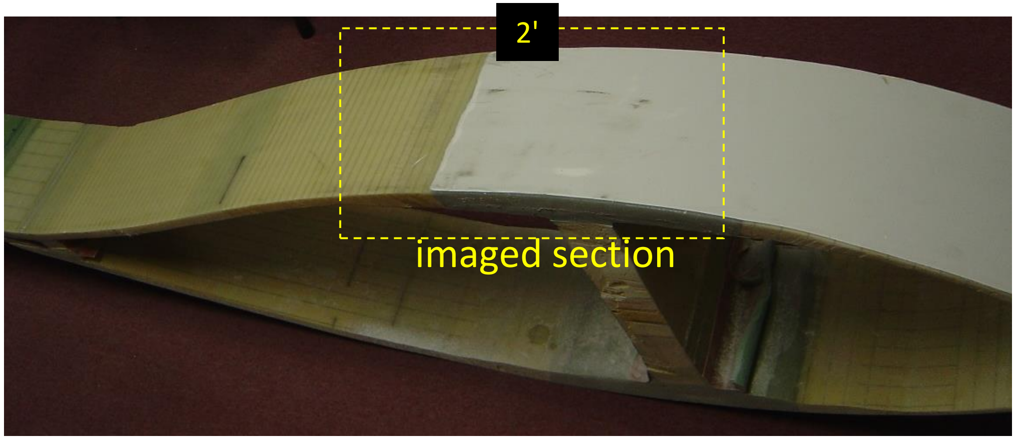
WRONG QUESTION!

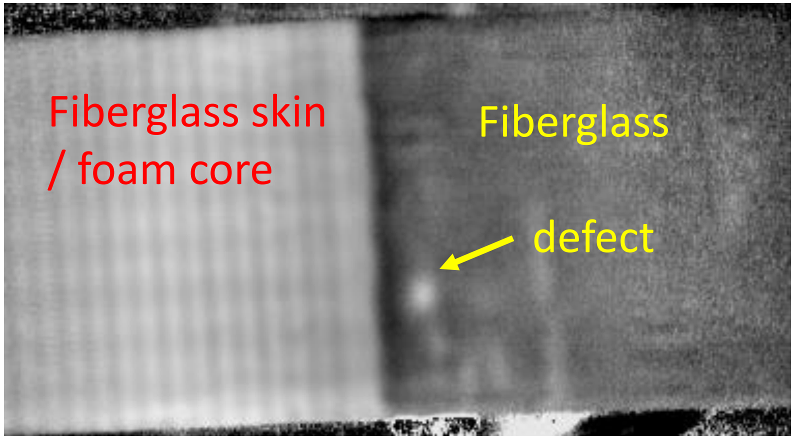
Field of View vs. Min Detectable Flaw Size

Q: What is the smallest defect I can reliably detect for a given area?

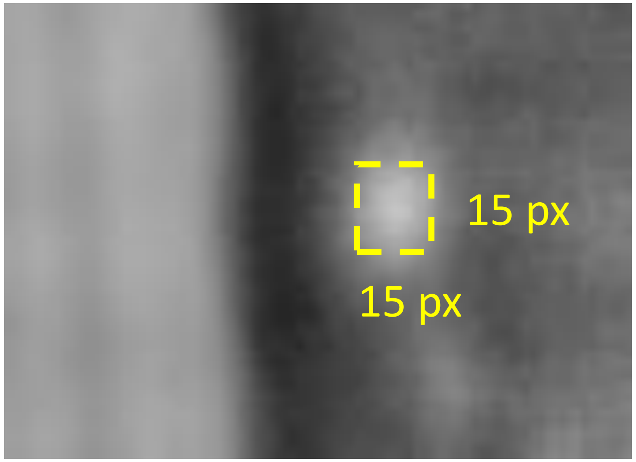
Q: How many pixels must cover that defect for high POD?

ASTM E2582-07: Minimum Flaw Size

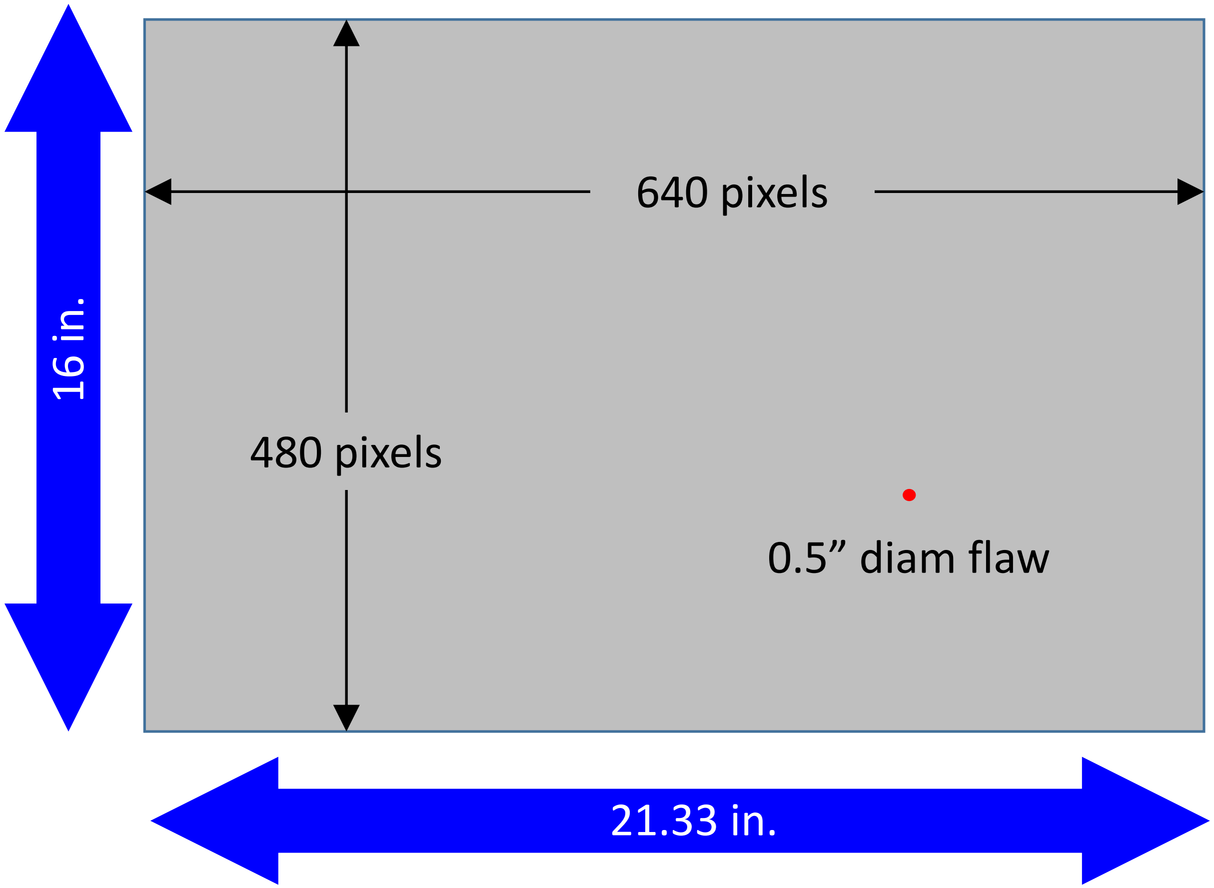




- ASTM E07-2582: min 9 pixels coverage for reliable defect detection
- 9 pixels is very low (std developed for 320 x 256 cameras, not 640 x 480 +)
- Field of view is determined by minimum flaw size, not size of target

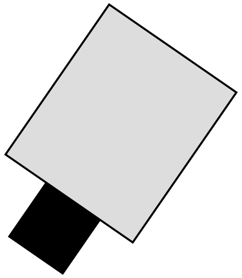


Example: 0.5” Min Defect Size



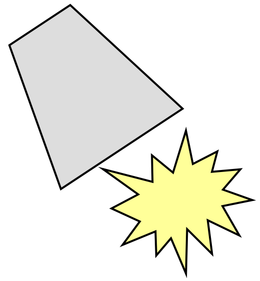
Maximum field of view to resolve a 0.5” flaw with a 640 x 480 pixel camera is 21” x 16”

Implementing Thermography



IR camera

Cooled / uncooled
Sensitivity
Resolution
Speed
Cost
Size / weight



Excitation

Optical
Convective
Direct contact
EM induction
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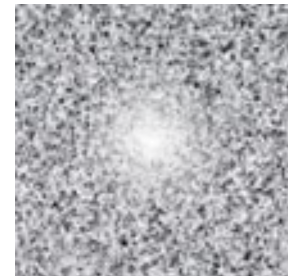
Solar

Pulse, step, scan…



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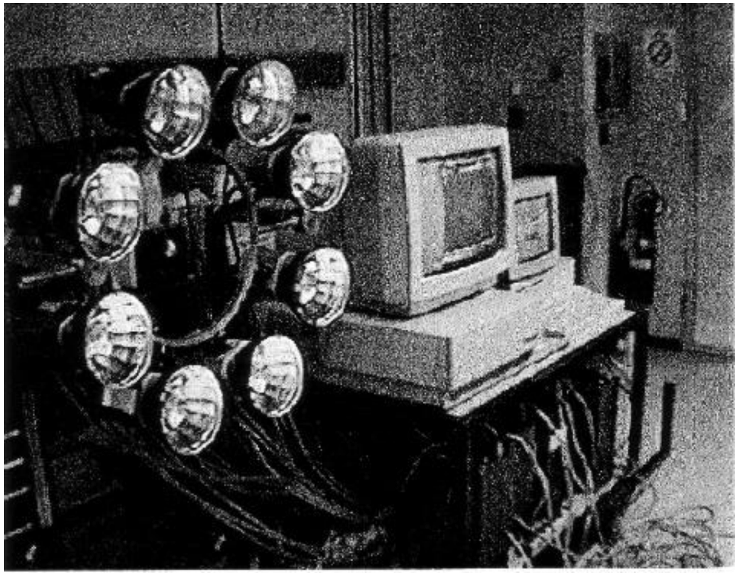
Excitation Energy Issues



Commercial flash system
- 1 sq ft area coverage
- 2 flashlamps (6 kJ ea.)
- Energy: 12 kJ

1992 system flash system
- 4 sq ft coverage (2 x 2’)
- 8 flashlamps (6 kJ ea.)
- Energy: 48 kJ
- Blew out hangar power
- Ignited nearby newspaper

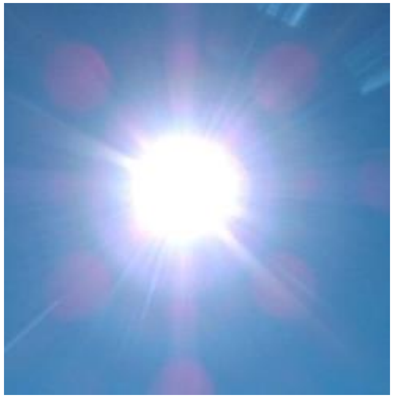
Excitation Choices

Flashlamp (4800 J)

Halogen Lamp (500 W)

Heat Gun (1800 W)

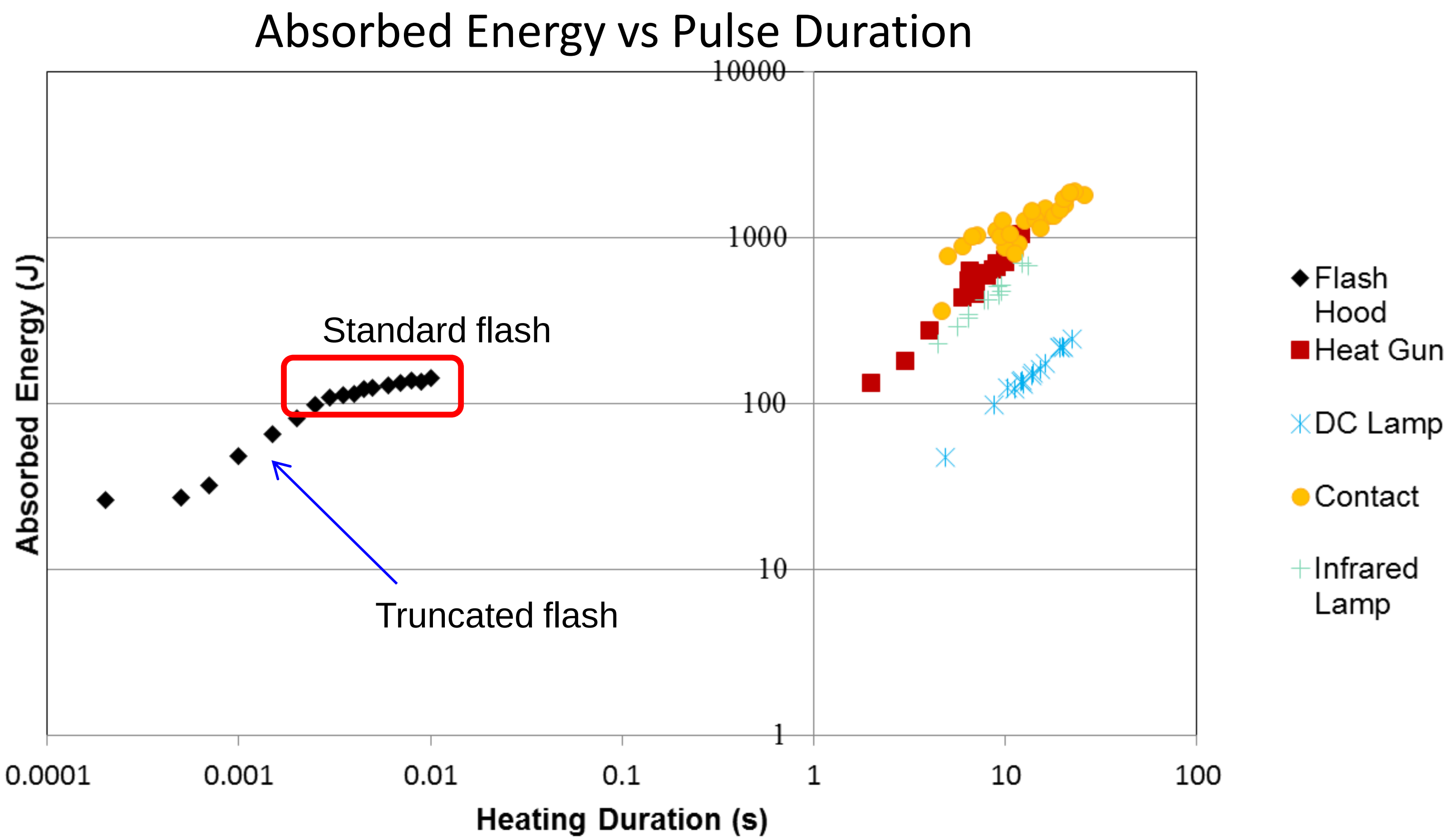
Heat Blanket (10 W/in^2)



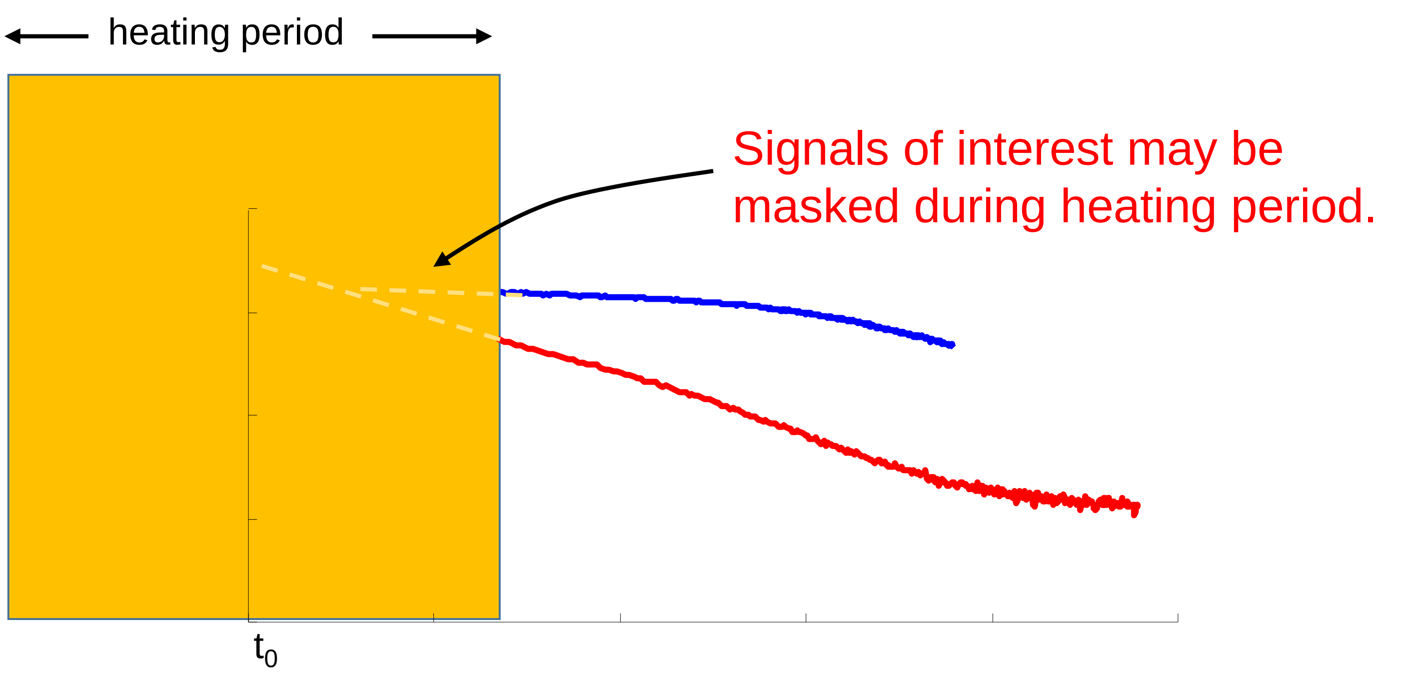
Solar heating (600 W/m^2)

IR Lamp (250 W)

Source Duration

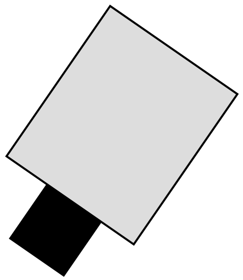


Extended Pulse Heating Tradeoff



Heating and cooling occur simultaneously during extended heating

Implementing Thermography



IR camera

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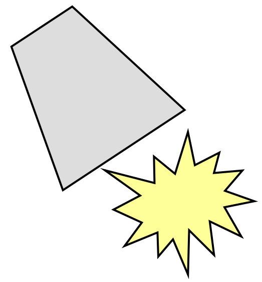

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Pulse, step, scan…

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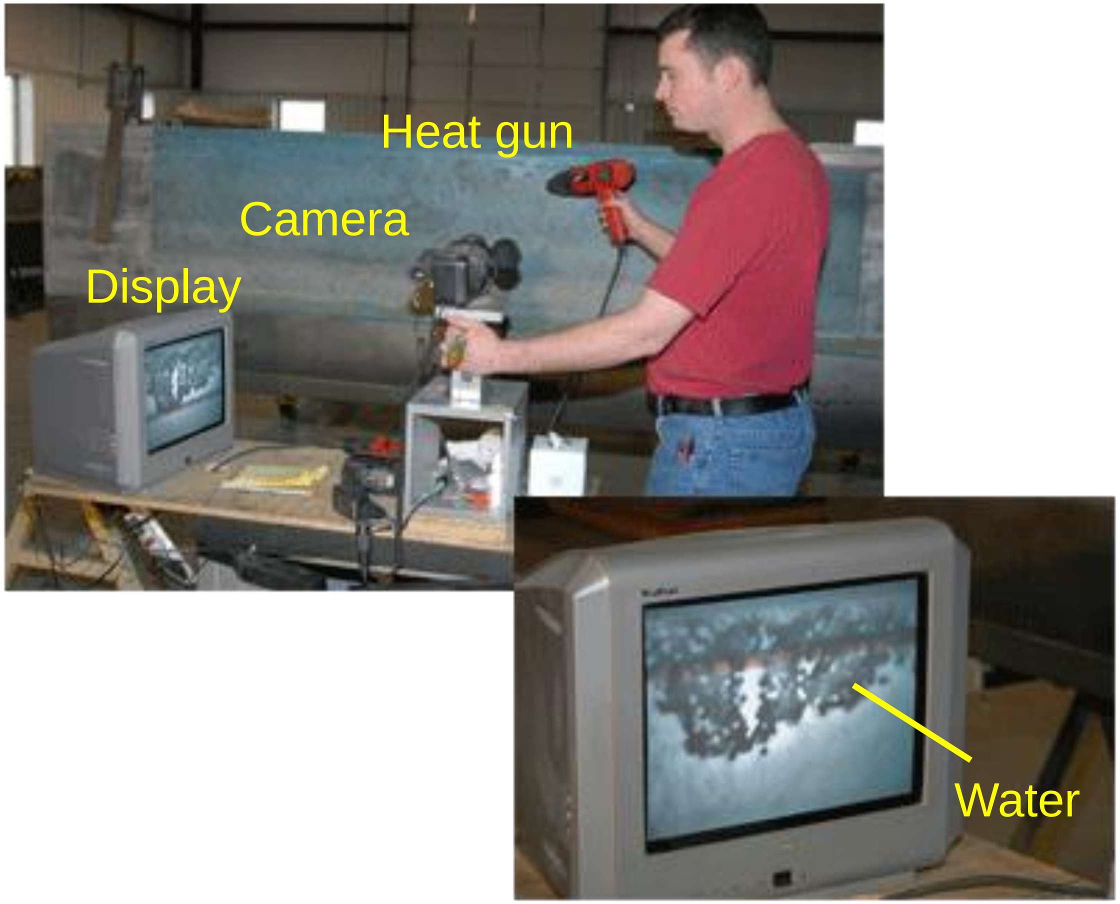
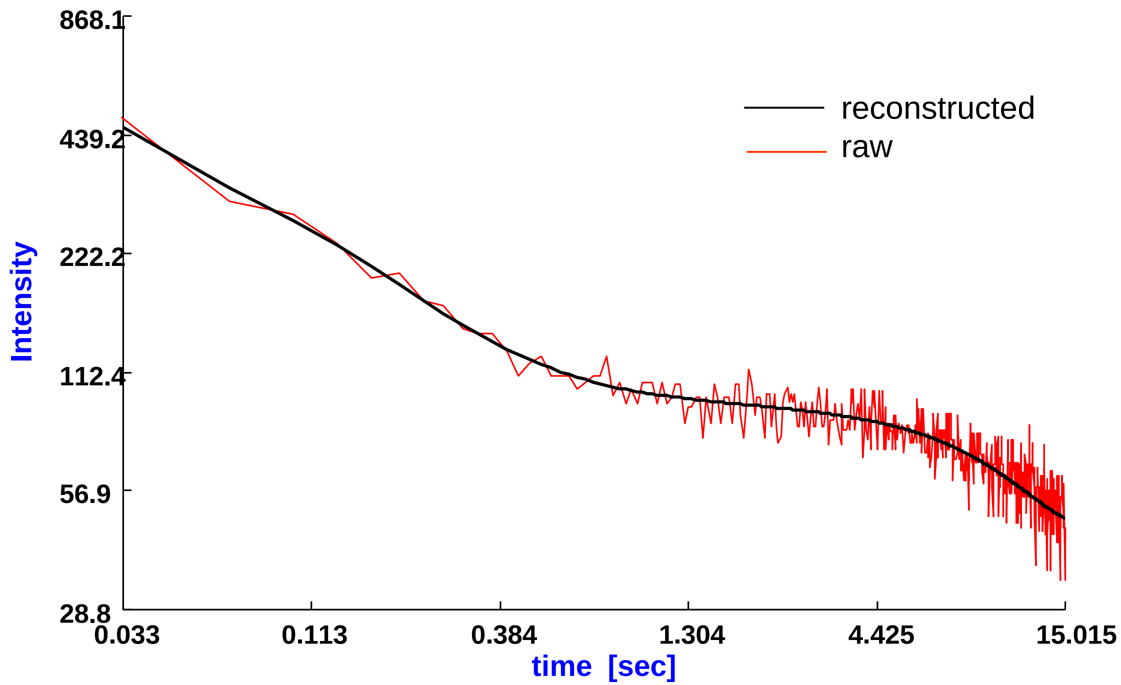
Thermography systems combine excitation, camera and image processing / viewing to match application requirements.

Qualitative Thermography: Water Entrapment



Thermographic inspection of CH-47 Main Rotor Blade using heat gun

Thermographic Signal Reconstruction (TSR)

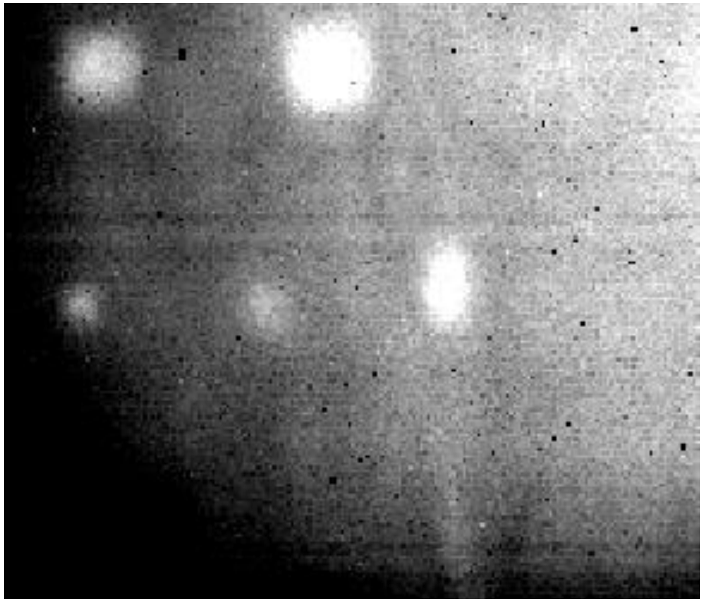


Original Concept (1999)

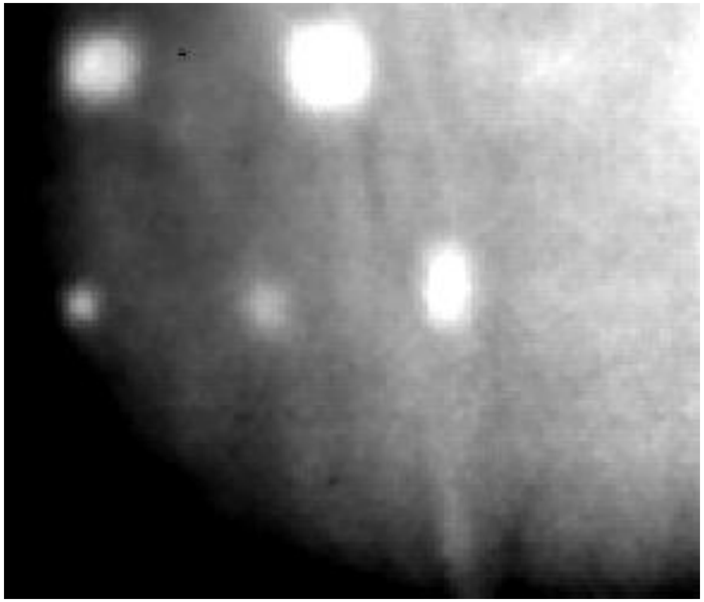
- Fit raw log-log data with a low order polynomial to reduce temporal noise
- Convert back to T-t after fit

Patent 6,516,084 (US), EP1258136 B1 (EU)

Temporal Noise Reduction



Raw

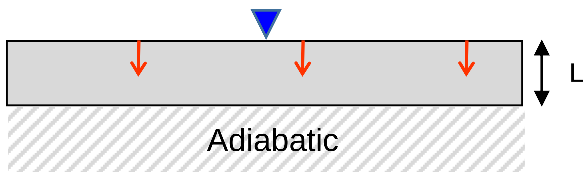


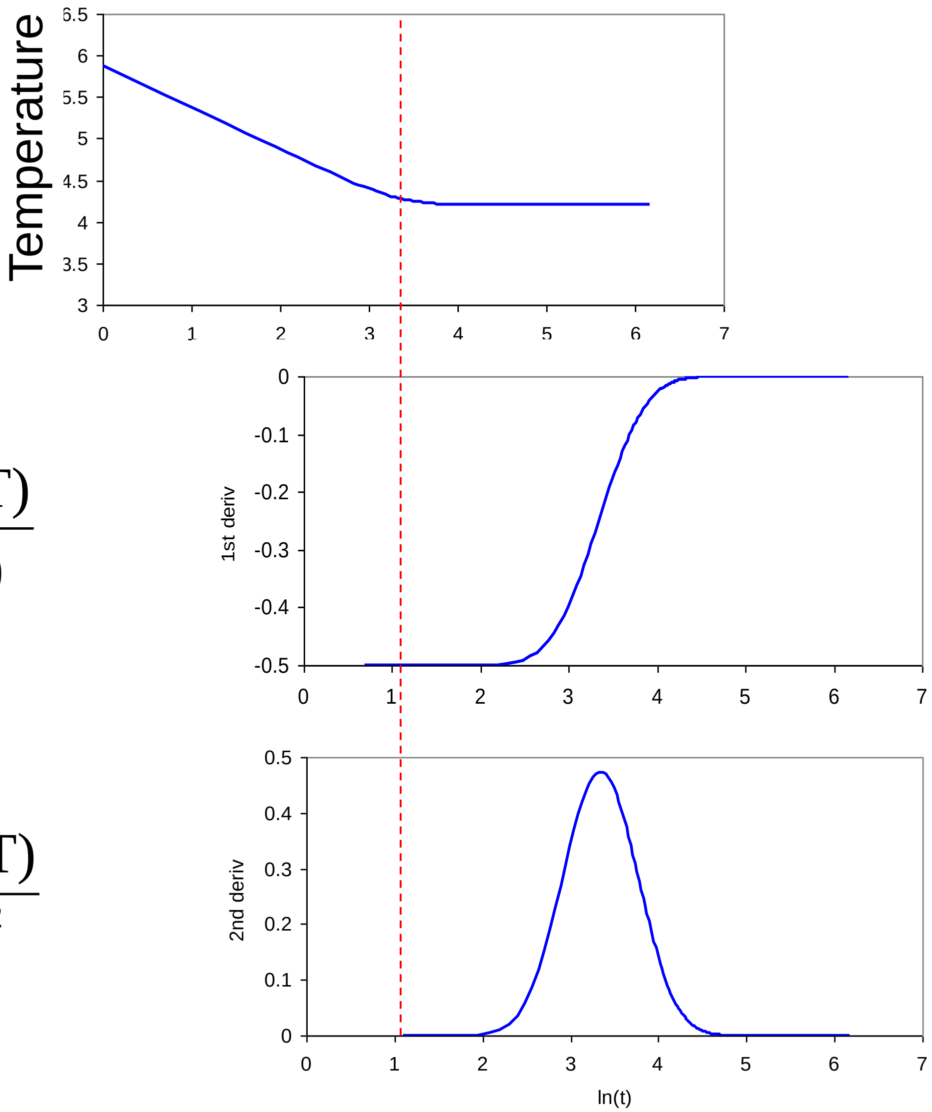
TSR

- TSR removes temporal noise from each pixel time history
- Lesson Learned: Noise reduction $\neq$ signal enhancement
- A prettier picture was not enough!

Data courtesy of D. Balageas, ONERA

TSR Derivatives of a Defect Free Slab



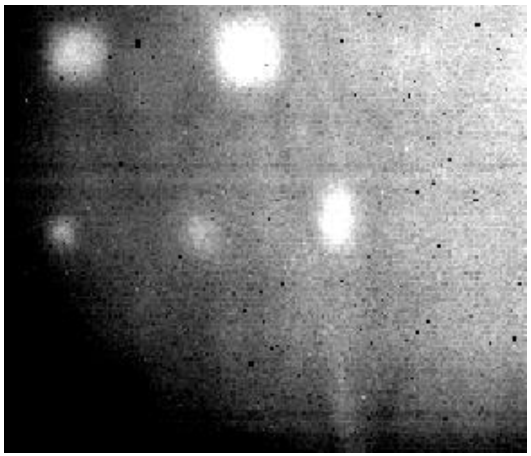


1st derivative: $$\frac{d\log(\Delta T)}{d\log(t)}$$

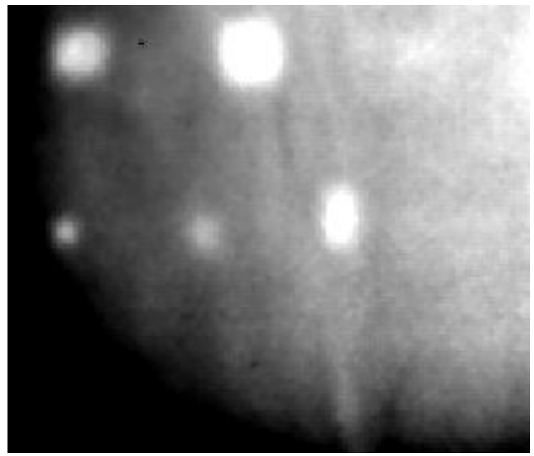
2nd derivative: $$\frac{d^2\log(\Delta T)}{d\log(t)^2}$$

Patent 6,516,084 (US), EP1258136 B1 (EU)

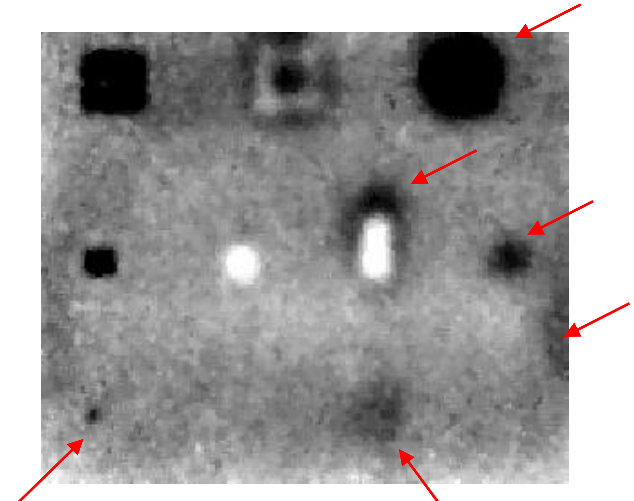
TSR Derivatives Improve Detectability



Raw



TSR



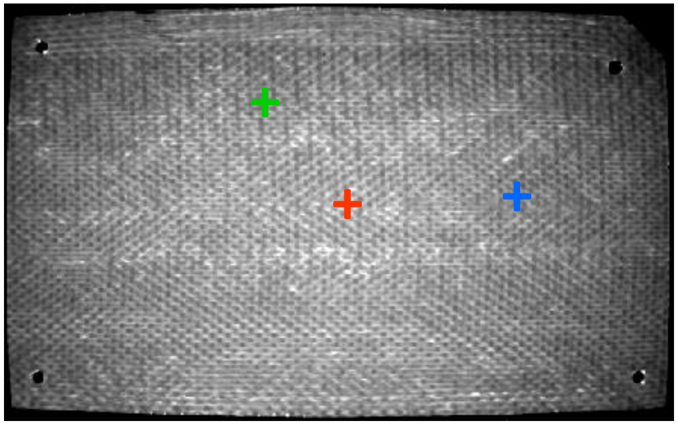
2nd Derivative

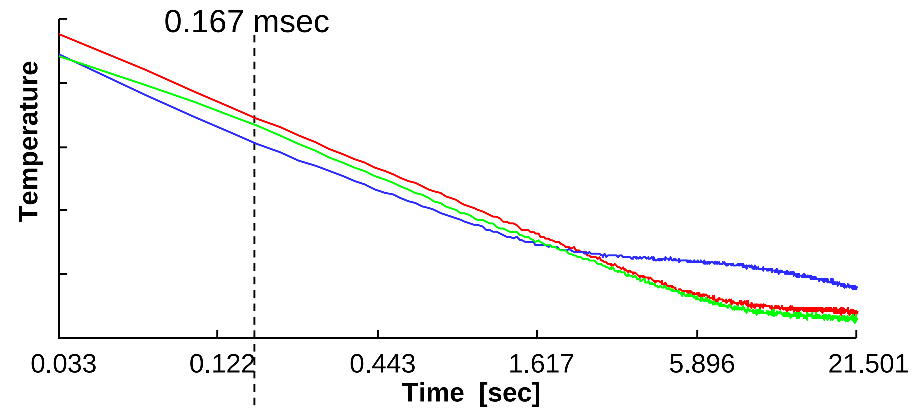
- Fitting provides noise reduction
- Derivatives provide signal enhancement

Data courtesy of D. Balageas, ONERA

TSR Derivative Time Sequence

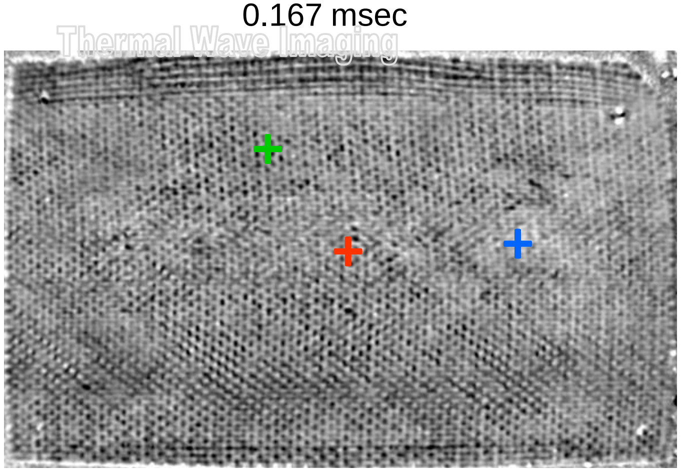
Raw

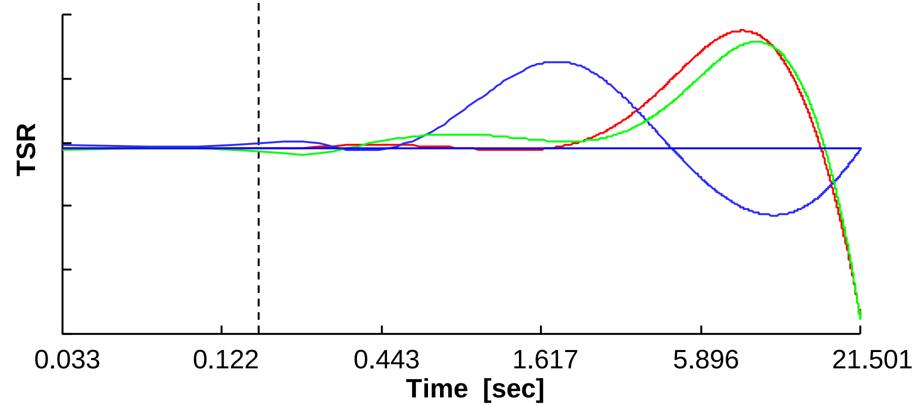




0.167 msec

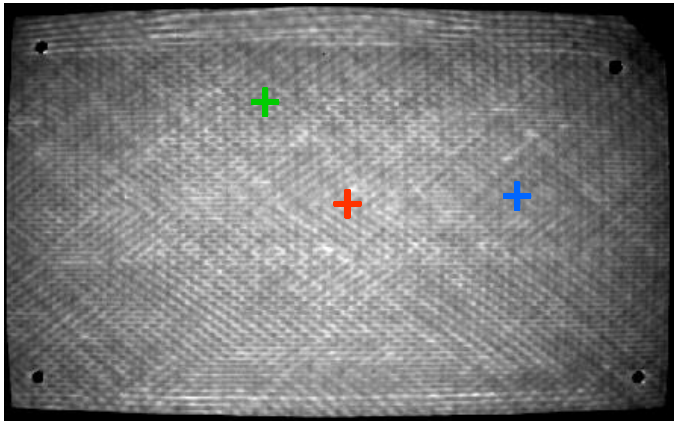
TSR 2nd derivative

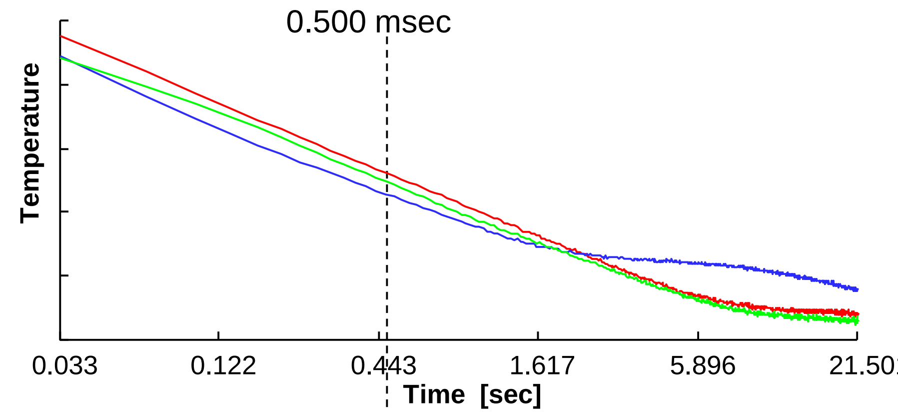




TSR Derivative Time Sequence

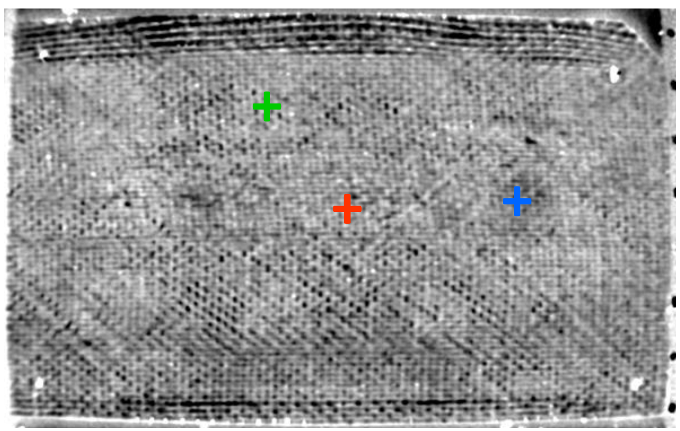
Raw

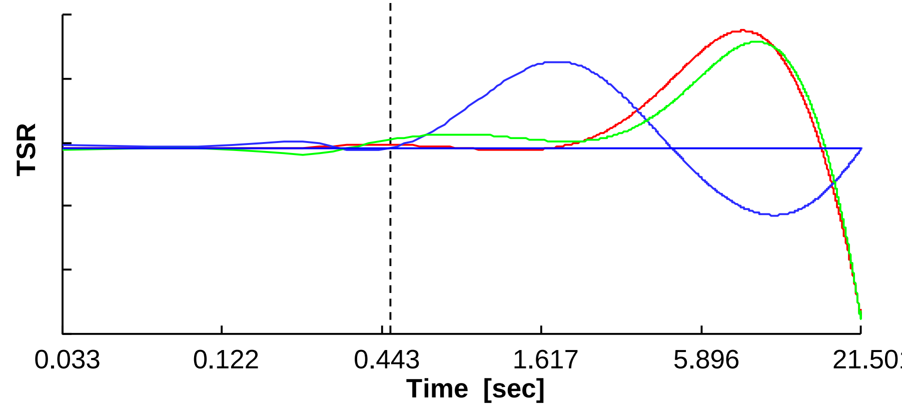




0.500 msec

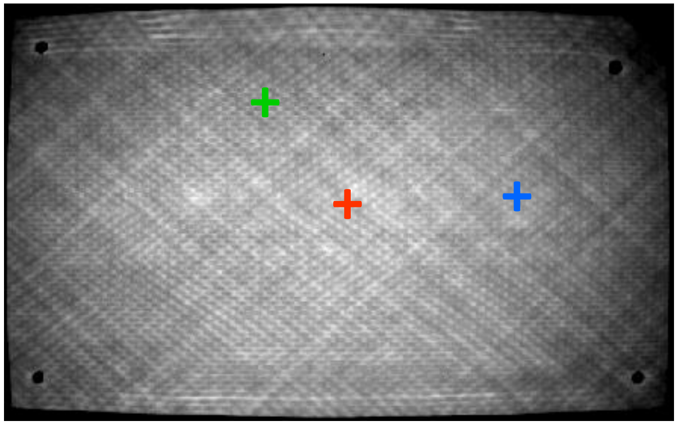
TSR 2nd derivative





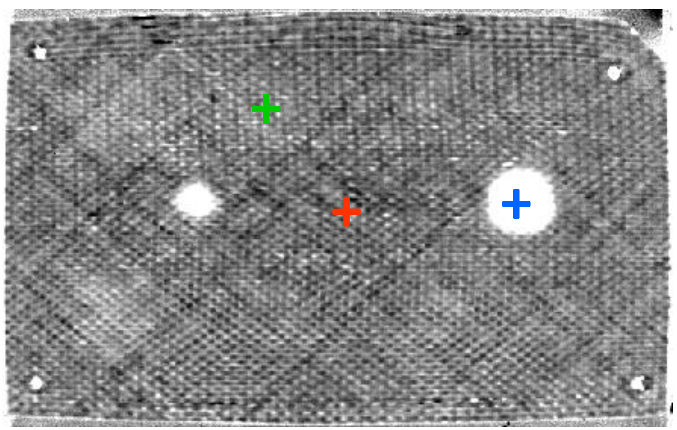
TSR Derivative Time Sequence

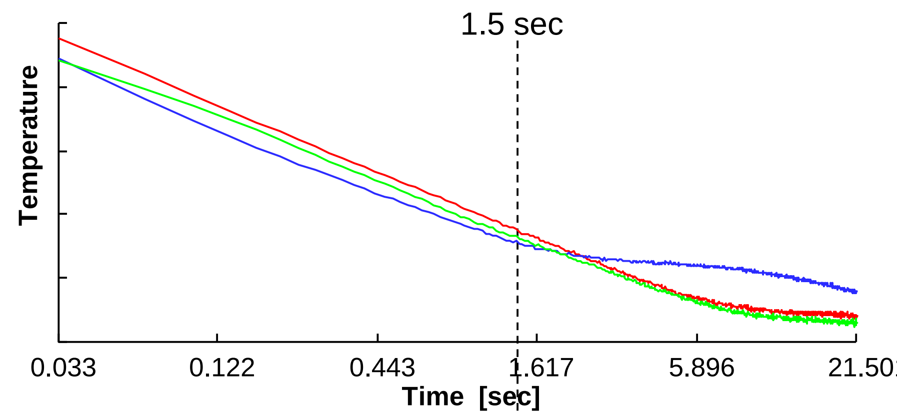
Raw

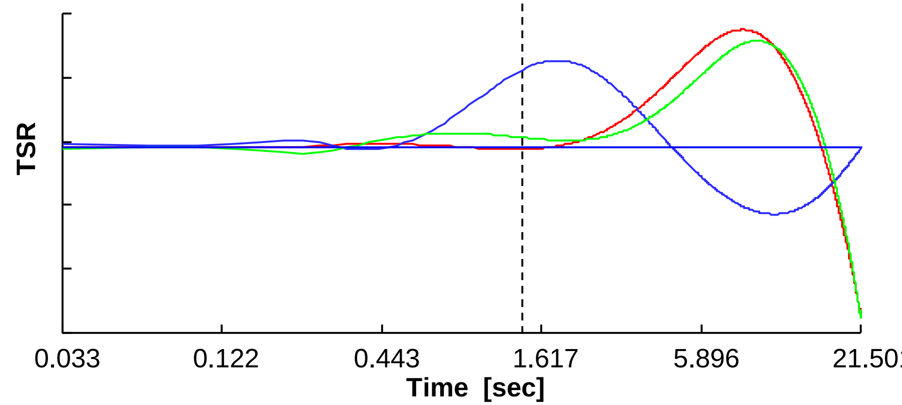


1.5 sec

TSR 2nd derivative







TSR Derivative Time Sequence

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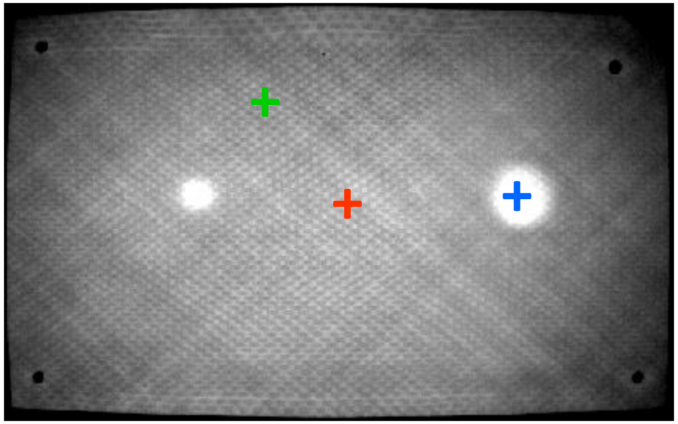
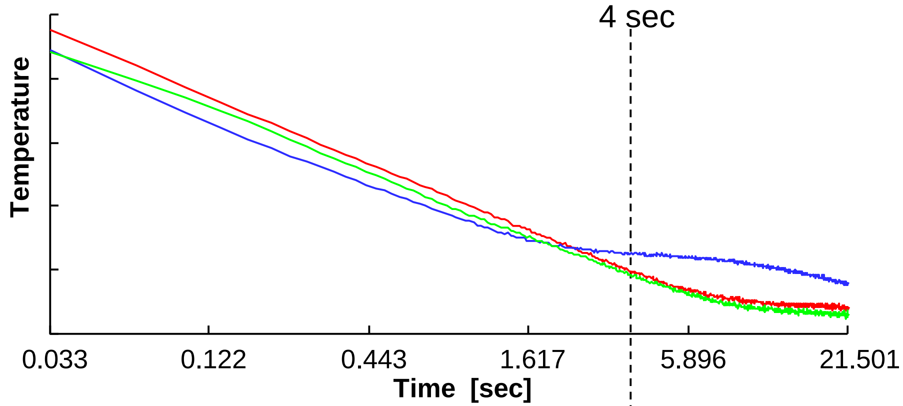
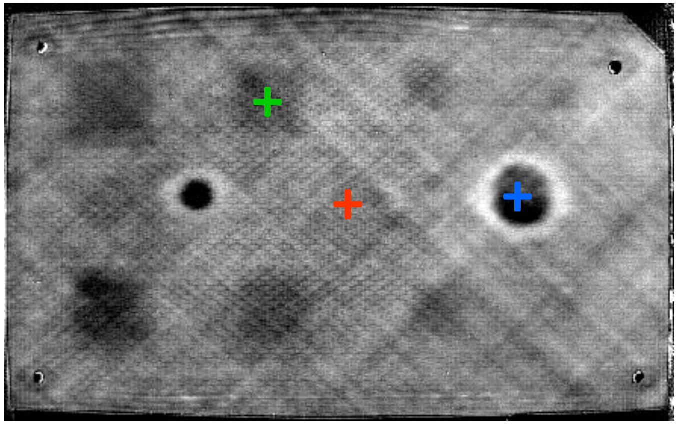
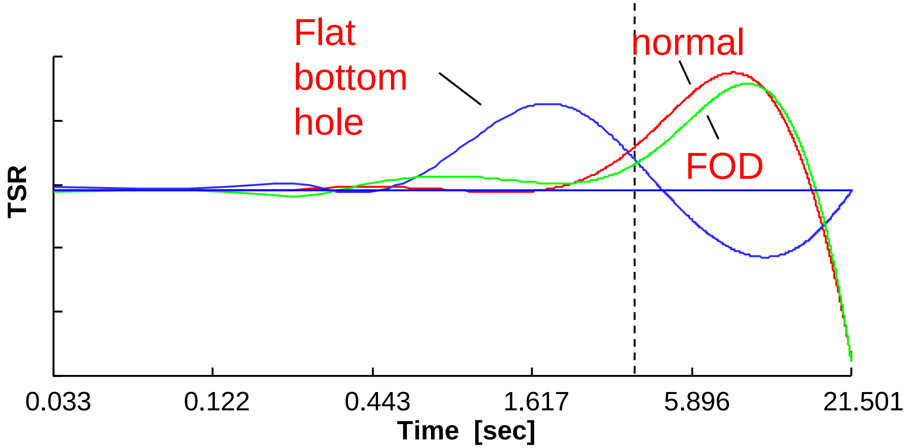




4 sec

TSR 2^{nd} derivative





Polymer film inserts at same depth as holes

Independent Validation- FAA POD Study 1

DOT/FAA/TC-15/4

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

A Quantitative Assessment of Advanced Nondestructive Inspection Techniques for Detecting Flaws in Composite Laminate Aircraft Structures

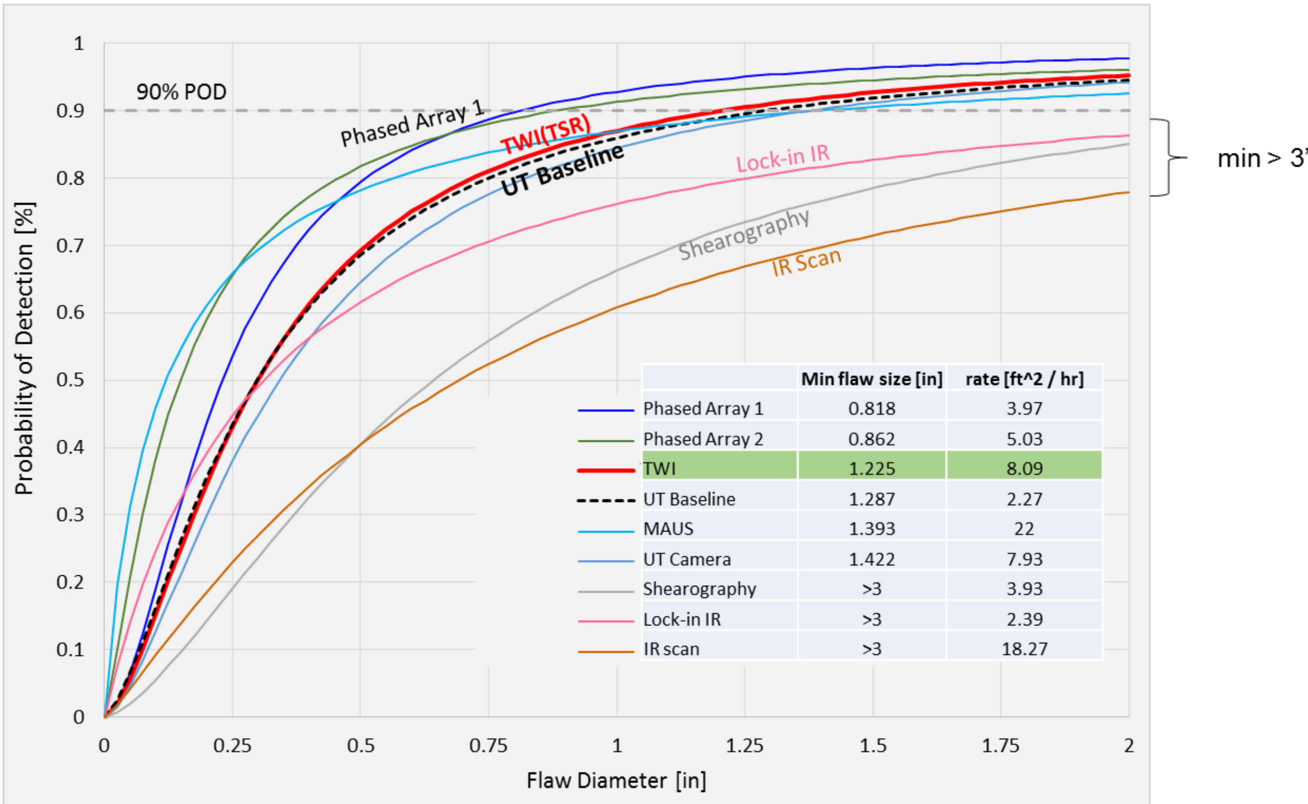
March 2016

Final Report

U.S. Department of Transportation
Federal Aviation Administration

Independent Validation- FAA POD Study 1

12-20 Plies: Constant thickness and complex geometry flaws



	Min flaw size [in]	rate [ft^2 / hr]
Phased Array 1	0.818	3.97
Phased Array 2	0.862	5.03
TWI	1.225	8.09
UT Baseline	1.287	2.27
MAUS	1.393	22
UT Camera	1.422	7.93
Shearography	>3	3.93
Lock-in IR	>3	2.39
IR scan	>3	18.27

Independent Validation- FAA POD Study 2

DOT/FAA/TC-15/63

Federal Aviation Administration
William J. Hughes Technical Center
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A Quantitative Assessment of Conventional and Advanced Nondestructive Inspection Techniques for Detecting Flaws in Composite Honeycomb Aircraft Structures

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Independent Validation- FAA POD Study 2

Of the advanced NDI methods, the top performers and 90% PoD levels for each category are listed below. In general, the level of improvement over conventional NDI methods becomes higher as the inspection challenge increases (i.e., skin becomes thicker and moves from fiberglass to carbon). The 90% PoD improvements range from 50–75% over conventional NDI methods.

- 3-ply fiberglass – Thermography and microwave ($PoD_{90} < 0.5''$ dia.)
- 3-ply carbon – Thermography, MAUS Resonance, Shearography, and AC-UT (PoD90 $< 0.5''$ dia.)
- 6-ply fiberglass – Thermography, MAUS Resonance, and Shearography UT ($PoD_{90} < 0.5''$ dia.)
- 6-ply carbon – Thermography and MAUS Resonance ($PoD_{90} < 0.5''$ dia.)
- 9-ply fiberglass – Thermography ($PoD_{90} < 0.5''$ dia.)
- 9-ply carbon – Thermography ($PoD_{90} < 0.5''$ dia.)

"Overall, when both 90% PoD levels and false calls are considered, thermography provided the best overall performance."

Large Area Inspection Tradeoffs

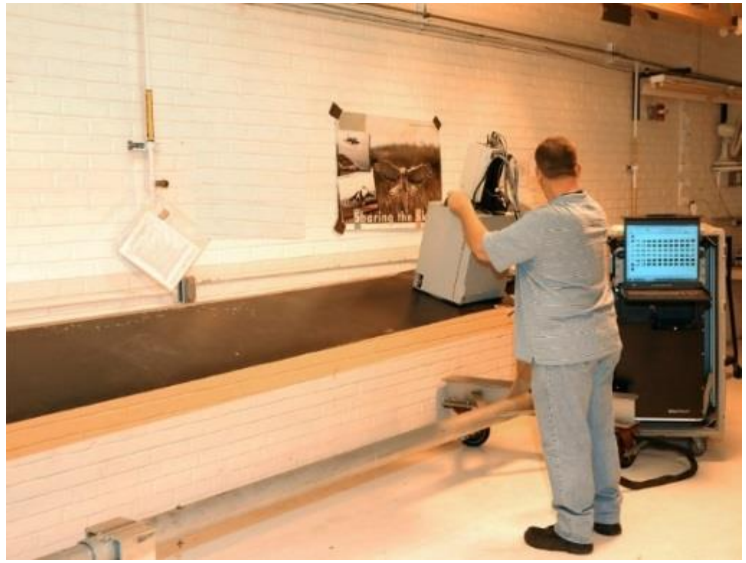
- Coverage area limited by minimum flaw size
- Processing required for sensitivity / quantitative analysis
- Source duration may interfere with processing

Priorities

- Sensitivity to flaws of interest
- Probability of Detection
- Inspection time
- Cost
- Ease of use

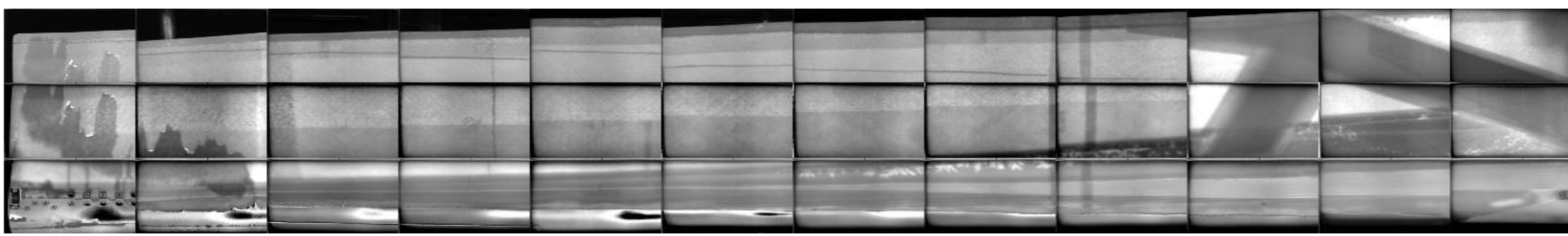
V-22 Proprotor Inspection: Flash Thermography

- 4 hours
- 36 shots
- Close proximity



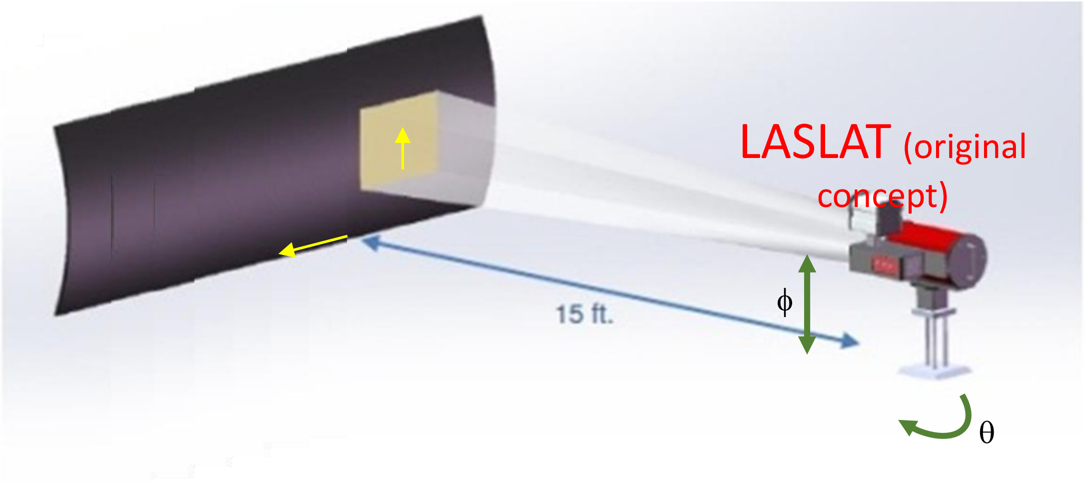
Current NDI of V-22 proprotor at FRC-E using TWI flash thermography system

21 ft



TSR processing of V-22 proprotor converts 36 shots into a single data set using TWI MOSAIQ software

Large Standoff Large Scale Thermography (LASLAT)

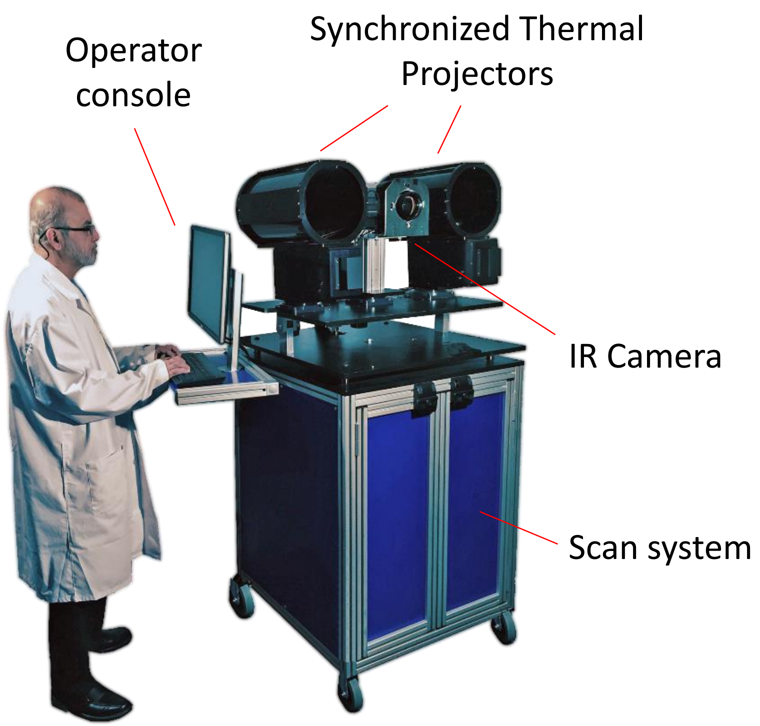


Objective: Provide the capabilities of flash thermography from a distance in a system optimized for NDI of large composite structures

- Minimize inspection turnaround time
- No gantry / robot or fixed installation required
- Easily adaptable for inspection of multiple platforms
- Simplify interpretation / analysis
- Operate in open hangar

Developed under NAVAIR Phase II SBIR N092-097

LASLAT Projection Thermography

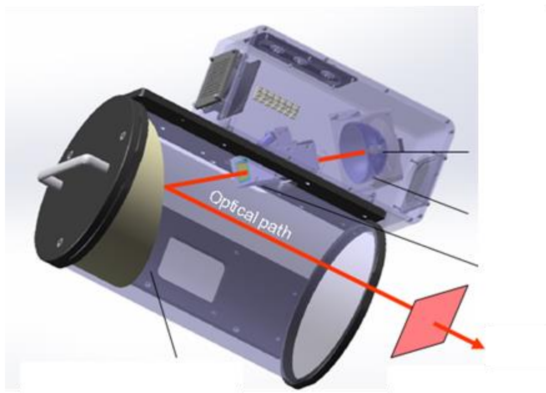


Working Distance: 10 – 15 ft
Single shot Field of View: 26 in x 21 in
Total Field of View: 17 ft x 15 ft (255 ft^{2})

Large area inspection from a fixed position

- Automated area scan
  - Produces single image of entire area
- Advanced signal processing
- No gantry, creeper or track
- Flat or curved surfaces
- Easily configured for new inspection

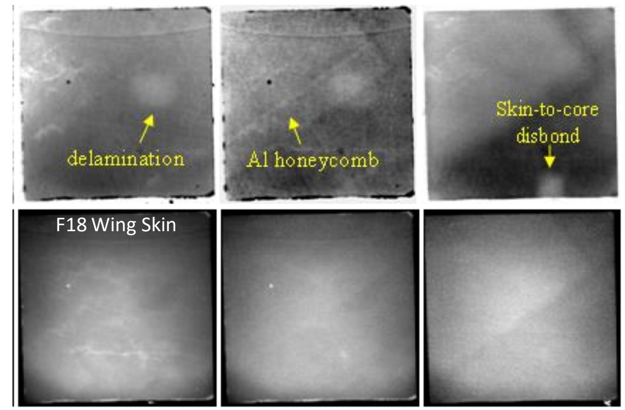
LASLAT Innovations



Novel thermal projection optical system for highest efficiency excitation

TSR processed

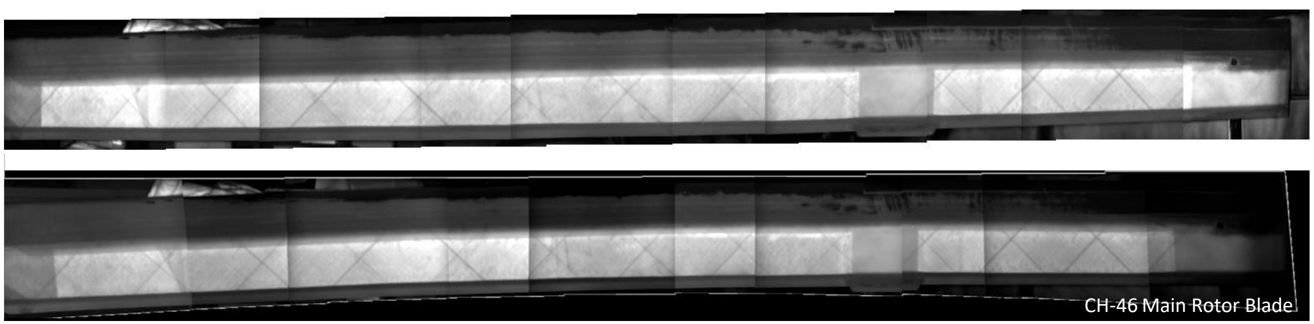
Unprocessed



LASLAT signal processing outperforms existing NDI for detection of fluid ingress and impact damage.

uncorrected

LASLAT corrected

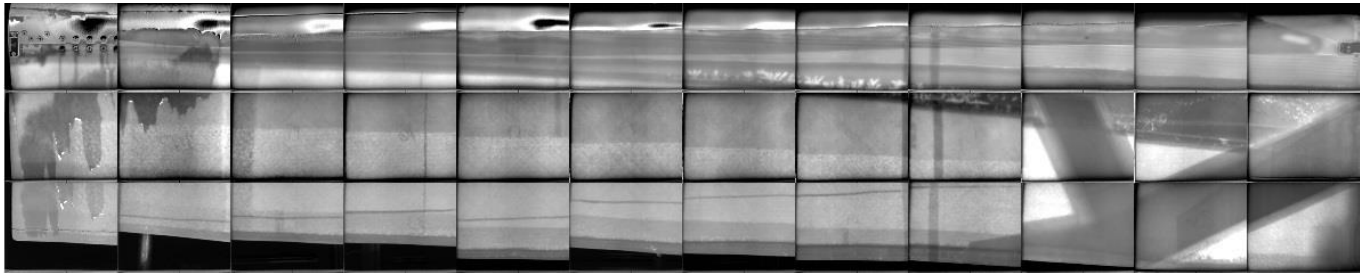


Optical correction over entire inspection field enables accurate defect sizing

Improvement to Current NAVIAR NDI

V-22 Proprotor Blade Inspection at FRC-E

Current: Flash Thermography

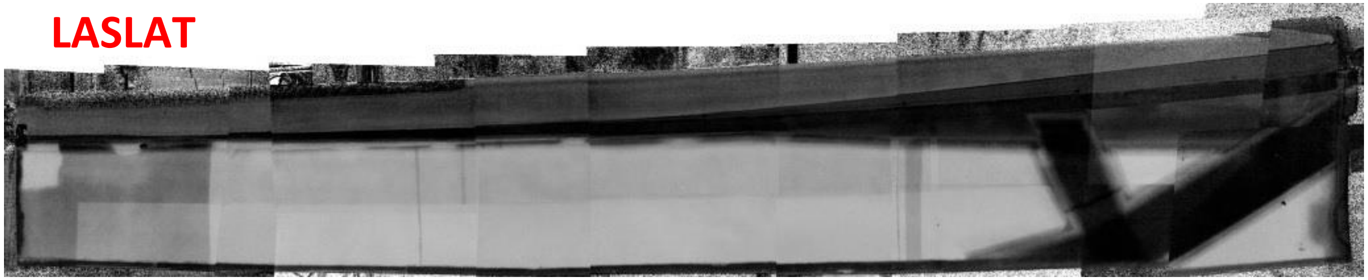


- 4 hours
- 36 shots
- Close proximity

System is manually repositioned after each shot

19 ft

LASLAT



- 9 minutes
- 18 shots
- 15 ft standoff

Blade is automatically scanned by system at fixed position

V-22 Fuselage Inspection at FRC-E

Automated scan of inspection area

V-22 Fuselage Inspection at FRC-E

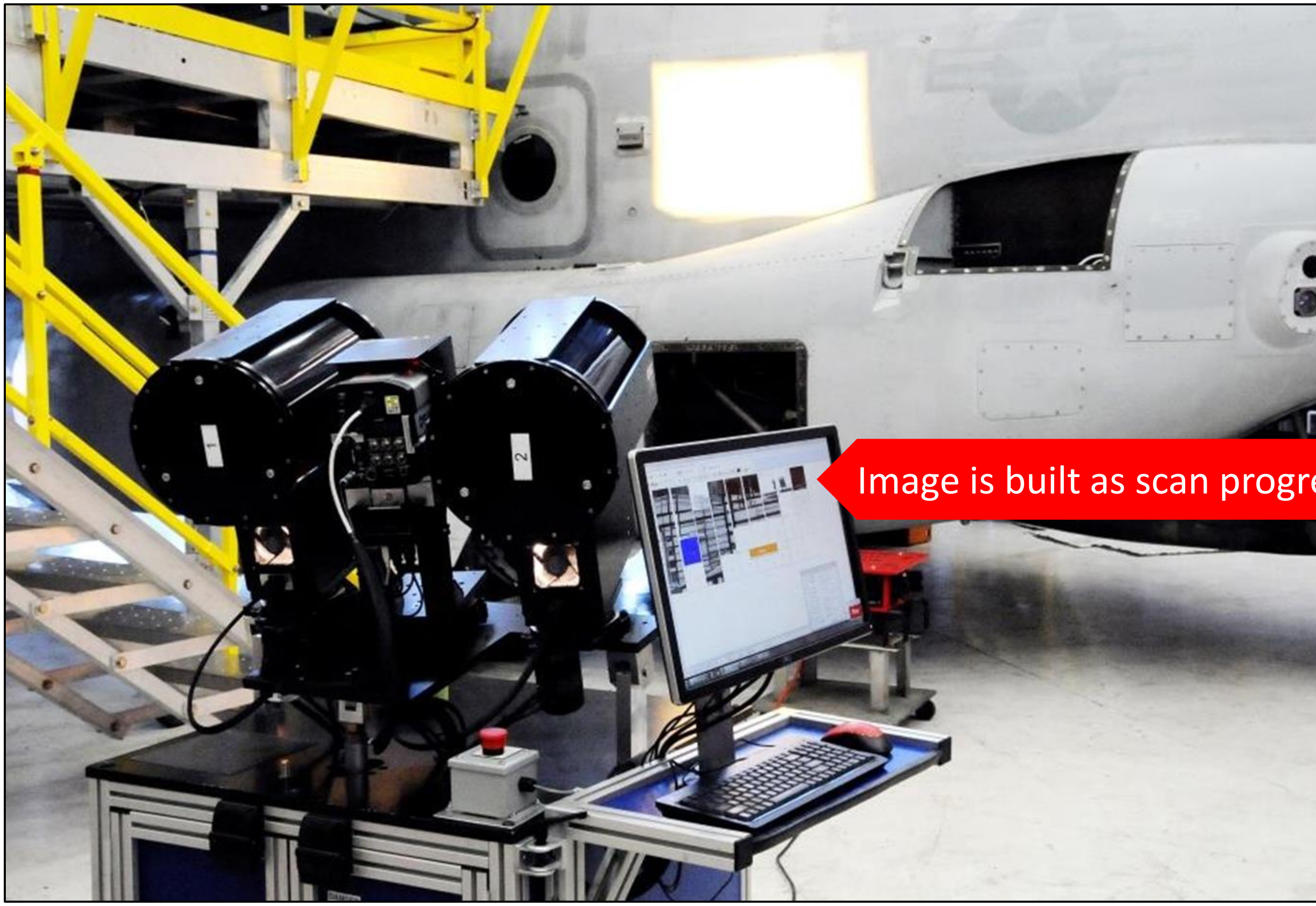


Image is built as scan progresses

Automated scan of inspection area

V-22 Fuselage Inspection at FRC-E

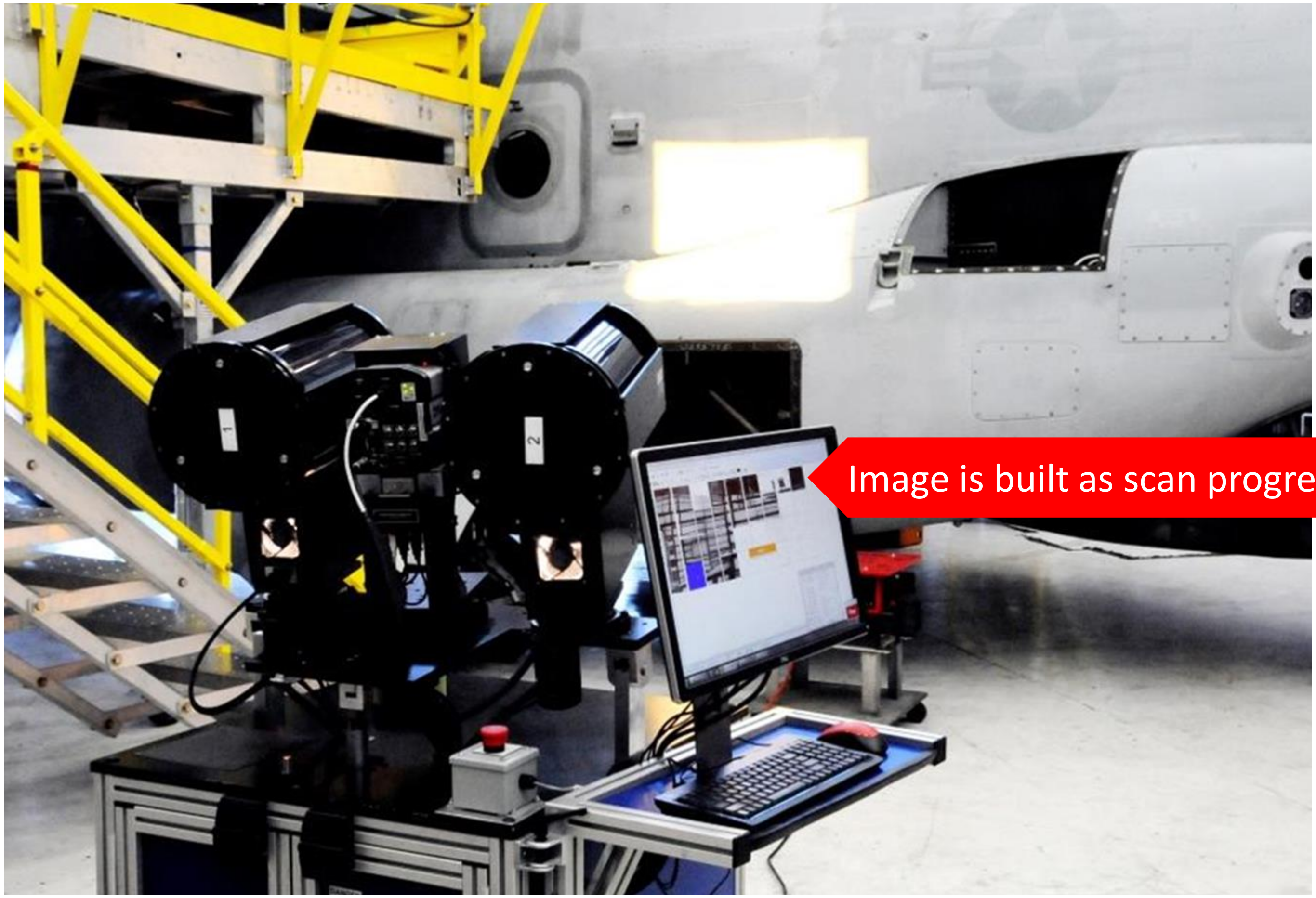
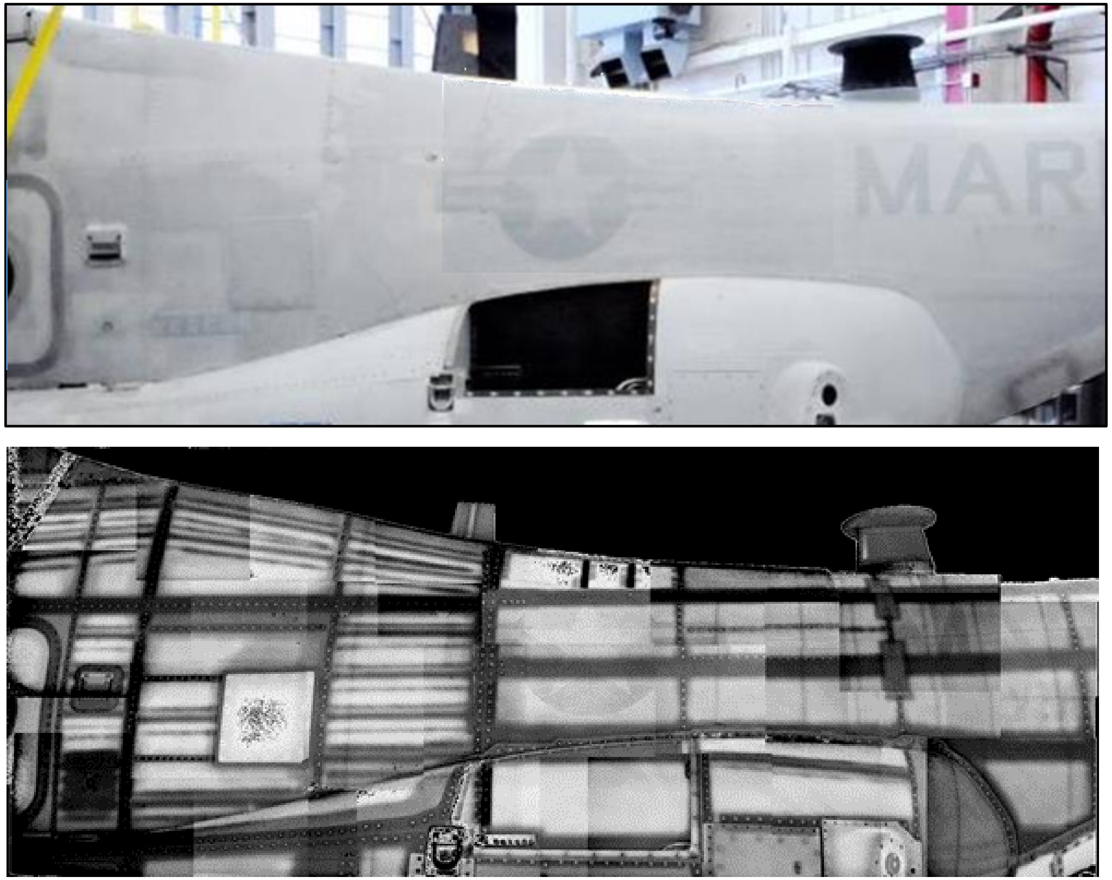


Image is built as scan progresses

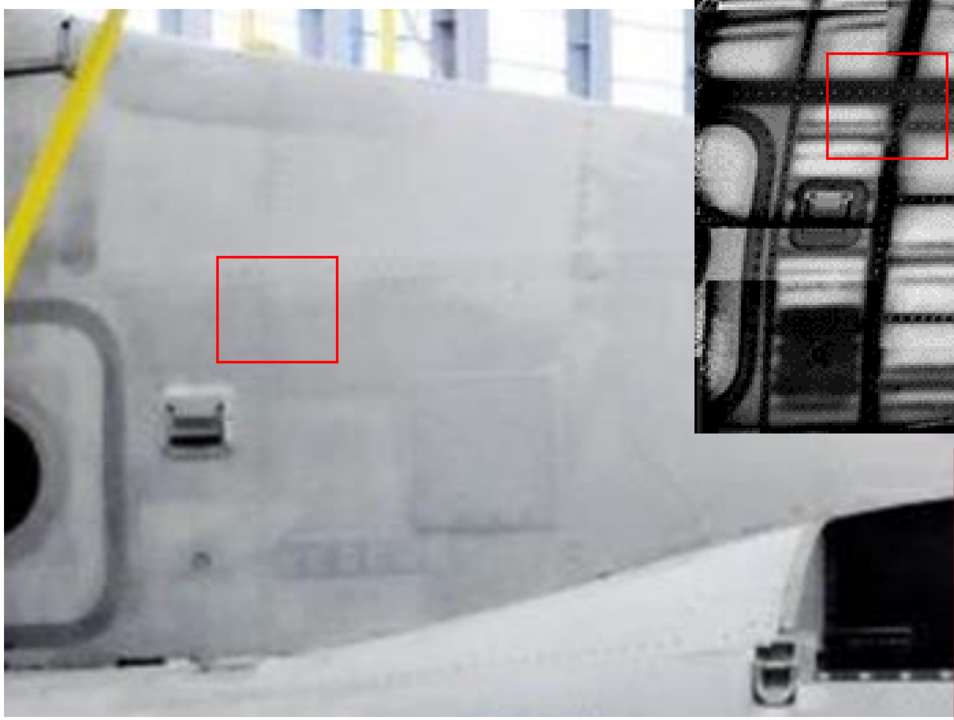
Automated scan of inspection area

V-22 Fuselage Inspection at FRC-E

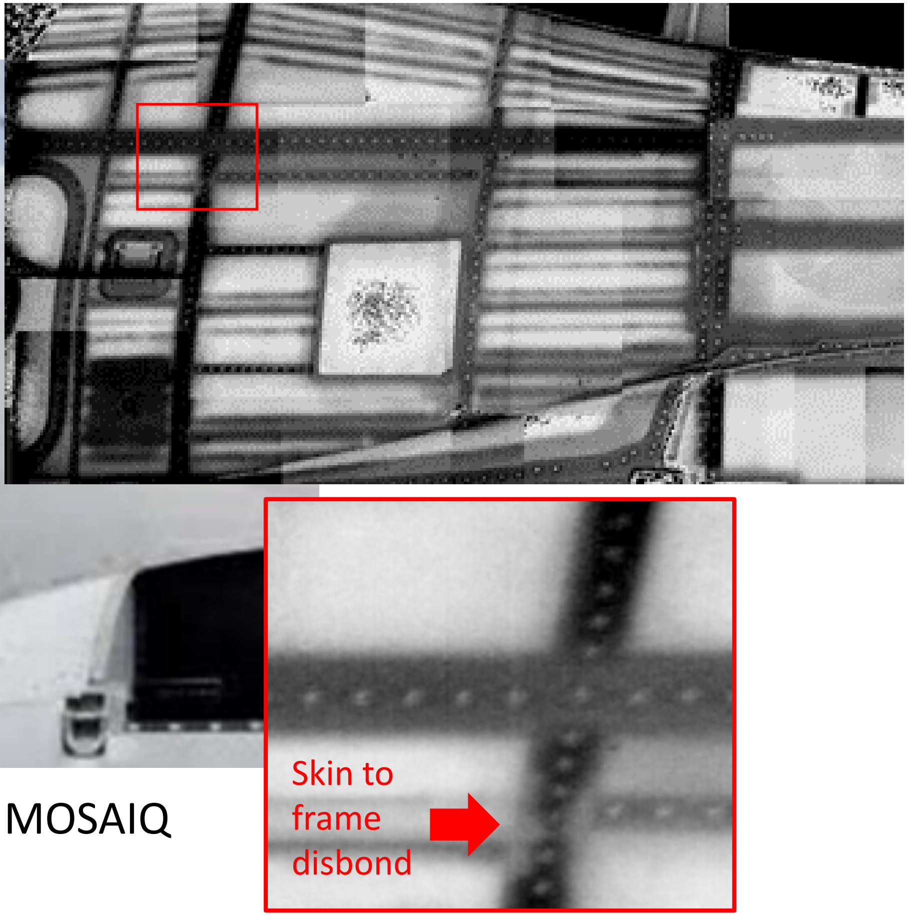


V22 Fuselage: 6’ x 15’ inspection area

V-22 Fuselage Inspection at FRC-E



Zoom view of inspection area in MOSAIQ



Improvements and Future Advancements

- Simultaneous processing and acquisition
- Real Time Processing / Analysis
- Real time FOD detection during layup

- Application Development
  - Repair ID and Validation
  - Through Transmission / Crushed Core
  - Heat Damage

Summary

- Min flaw size dictates max field of view
- Tradeoffs between optics, energy and POD
- LASLAT
  - 80 sq ft / 9 min
  - Configurable to range (50 ft max to date)
  - TSR signal enhancement and data reduction
  - Transportable – no infrastructure required
  - Automated area scan