Space-Based Sensor Enhancement By Signal Processing

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Acknowlegements

- JSC/ES: George Studor (Overall)
- JSC/KX: Michael Rollins, Ed Oshel, Donn Liddle (Image Analysis and Image Processing)
- JSC/EV: Michael Grygier (Vibrometry)
- LaRC: Eric Maderas (Radar)
- GSC: Justin Cassidy (VIPIR)
- Sandia National Laboratories (LDRI)
- Pacific Northwest Laboratories (Radar)

Examples to be covered

1. “SURVEY” Inspection to Detect Damage
   – Rapid, preplanned coverage of large areas
   – Detect possible holes, cracks for focused inspection
2. “FOCUSED INSPECTION” to Quantify Damage
   – Extended-time coverage of detections
   – Measure damage depth/volume, especially at critical subsurface layers
3. “VIBROMETRY”
   – Remotely measure modal response of structure
      • Validate structural models
      • Detect damage-induced changes

Application 1: SURVEY

- Closed Circuit TV video was used for Shuttle Survey
  - Rapid area coverage, real-time downlink, many remote camera stations (including SSRMS)
- Desire for higher resolution is constrained by existing data transmission hardware
  - Incentive to enhance imagery via software, if possible
- Examples in following slides
  - Shuttle Leading Edge Inspection, STS114 – STS135
    - LDRI video (an intensified camera)
  - International Space Station video
    - Color TV video
    - VIPIR video

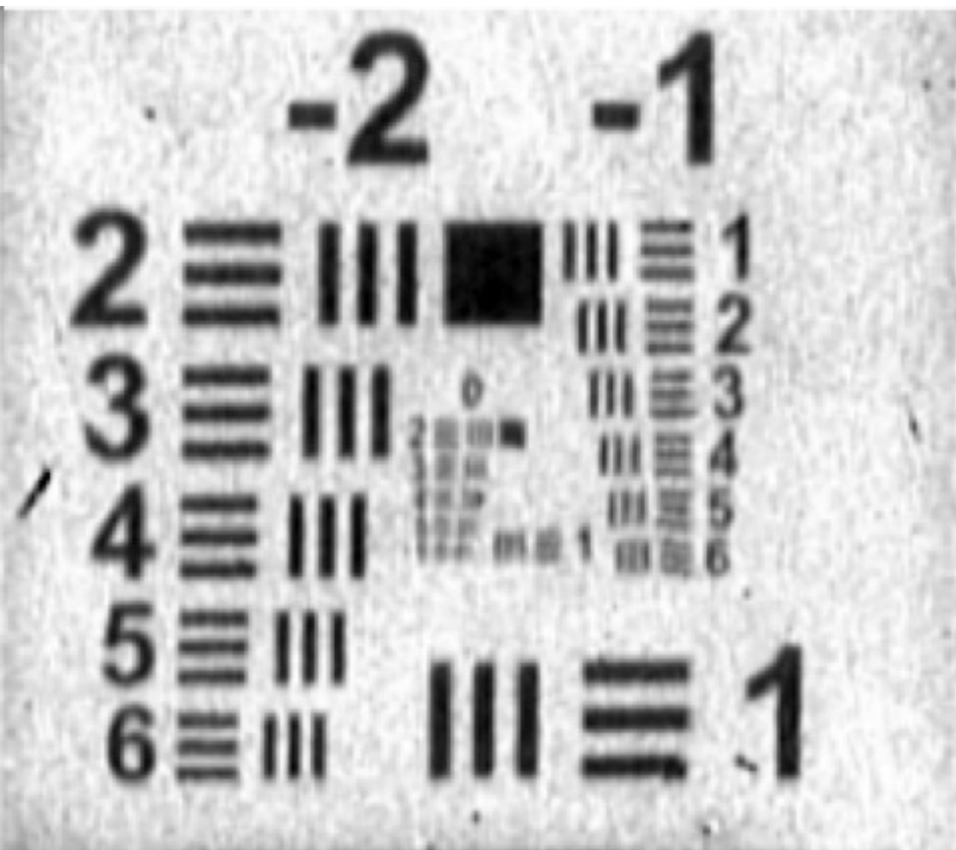
Image Enhancement Examples

- Pixel Gain and Offset Correction
- Camera distortion correction
- Motion stabilization and multiframe averaging
- Inverse Blur correction
- Super resolution

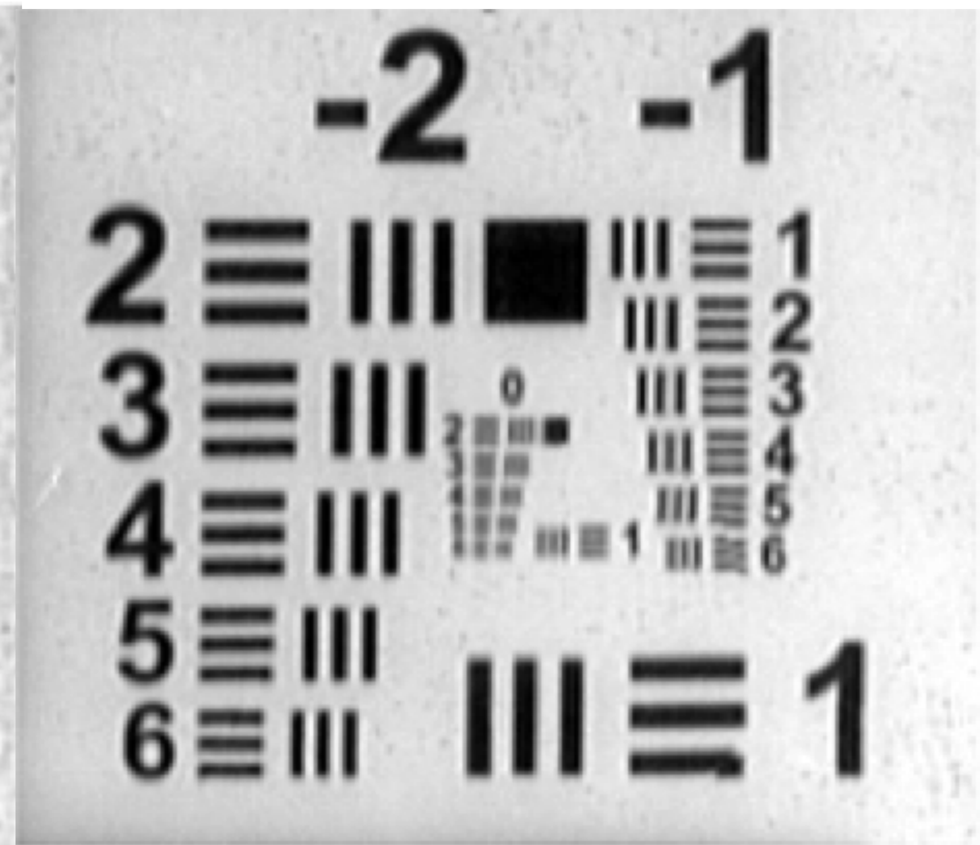
PIXEL GAIN AND OFFSET CORRECTION

Applied to LDRI CAMERA

RAW



CORRECTED

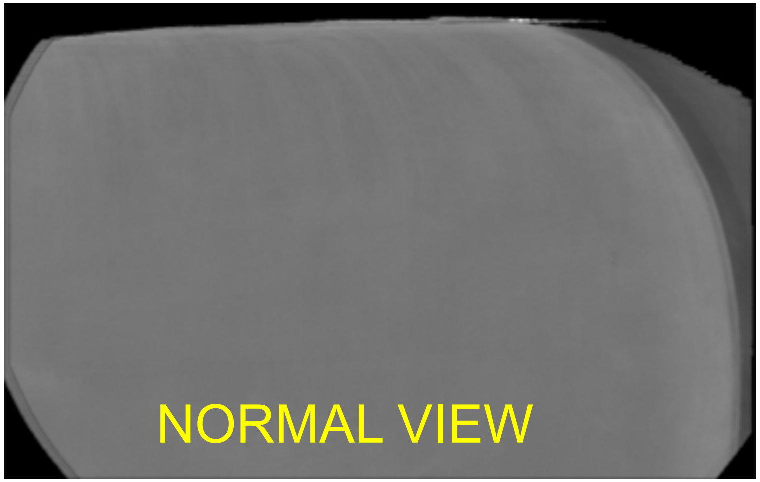


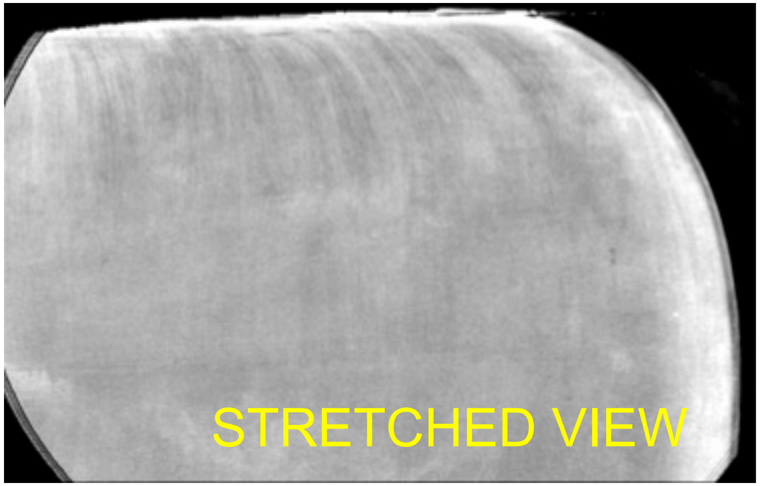
DISTORTION CORRECTION

- Distortion causes straight lines to appear curved
- Desired for photogrammetry or highly distorted images
- Corrected using calibrated distortion parameters
  - Brown's Distortion Model
  - Laboratory calibration or data-driven

Multi-frame Averaging + Contrast Stretching
(LDRI Camera)

- Normal pixel intensity is 8-bits, with noise
- Averaging improves intensity resolution with fractional resolution and reduced noise

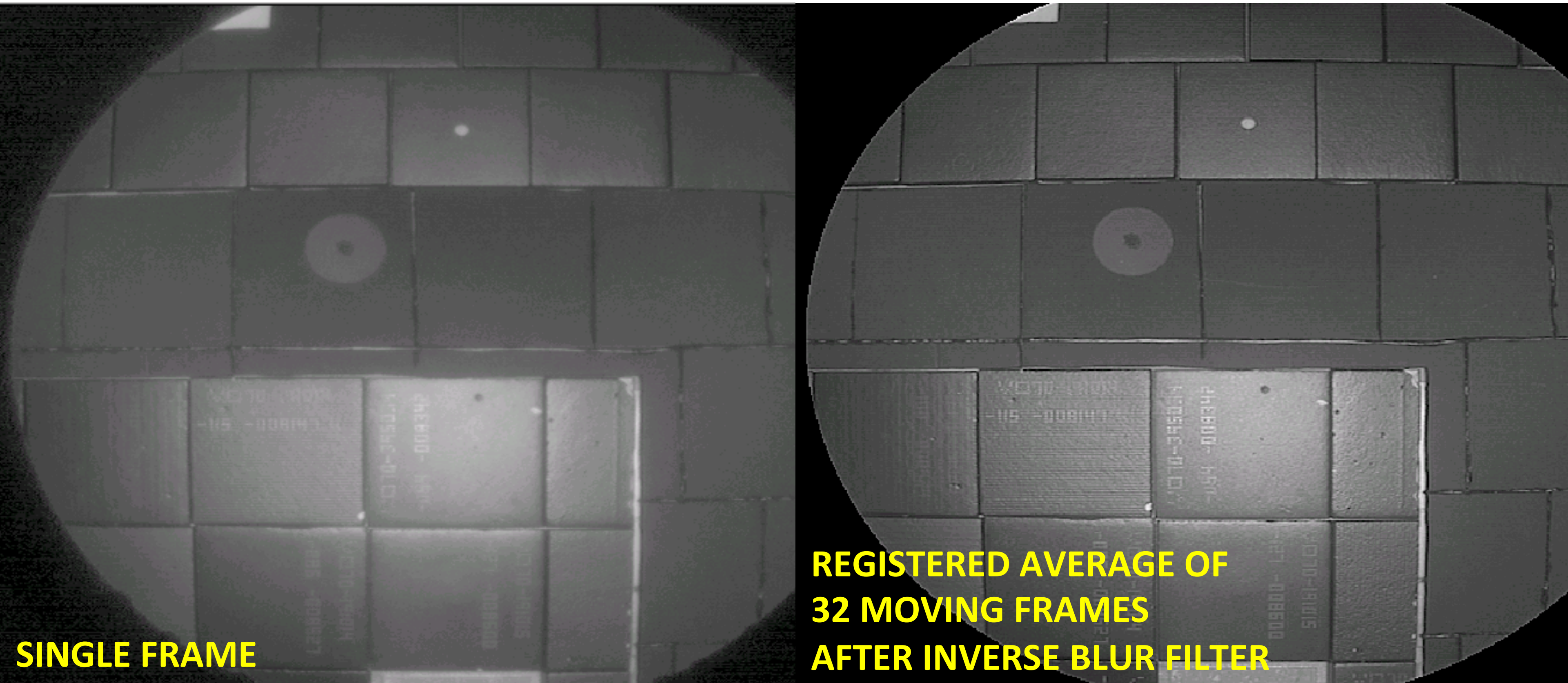




- On orbit inspection of OV-103 Port Panel 10 (RCC)

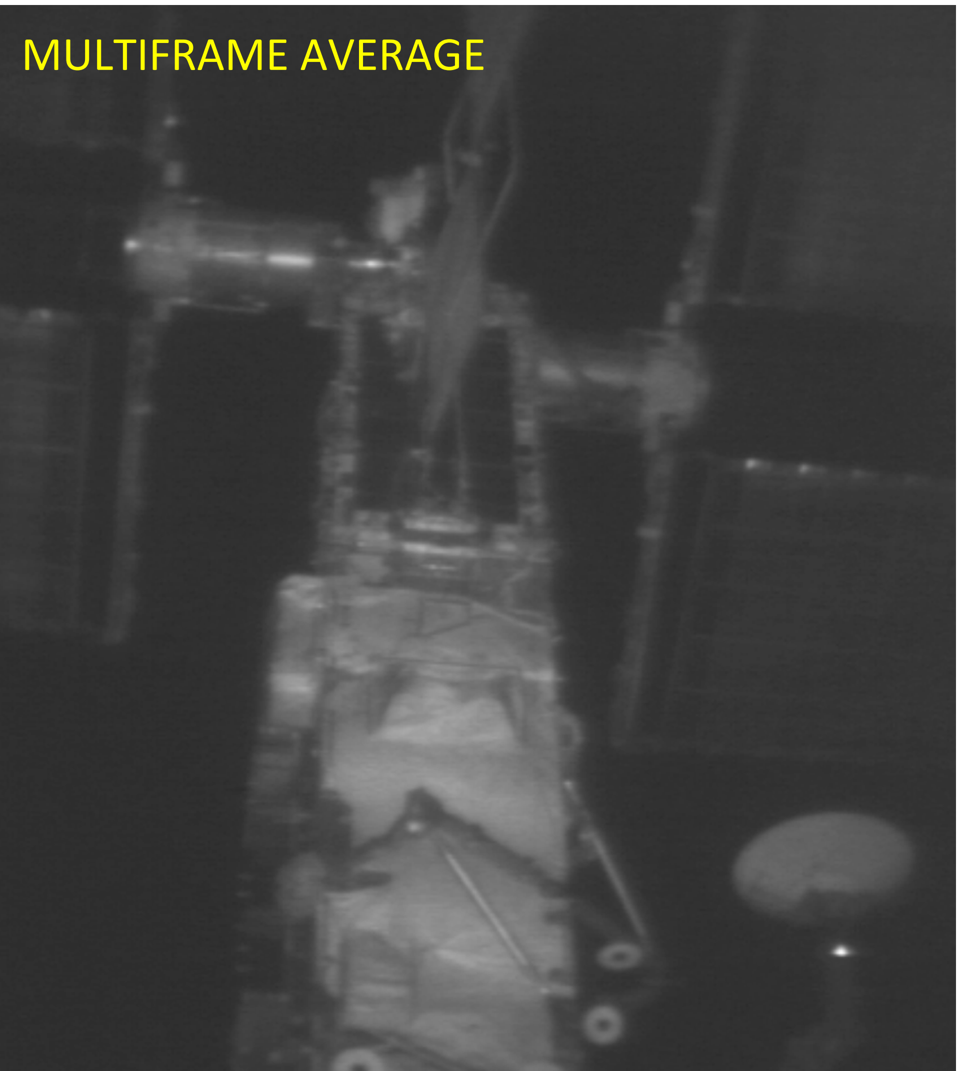
Multi-frame Averaging + Filtering (LDRI Camera)

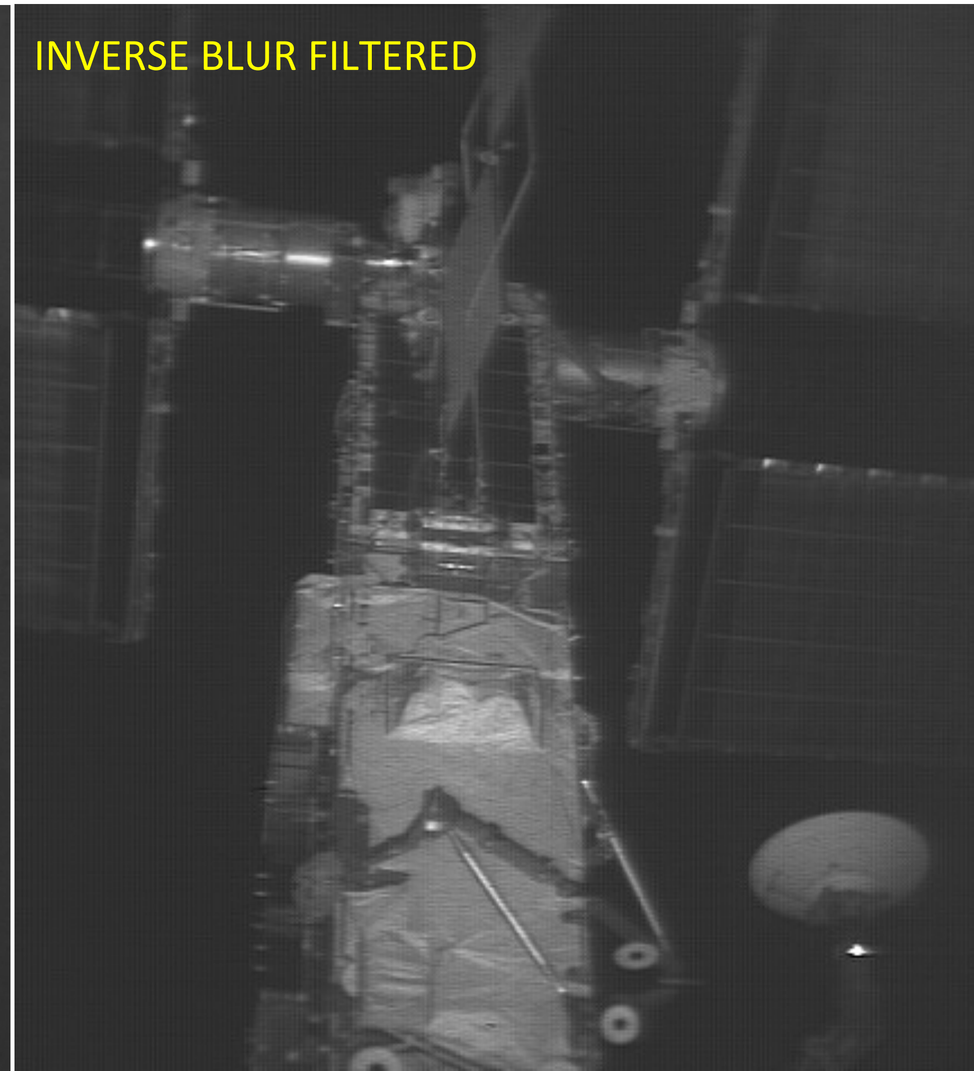
- Reduced noise/aliasing improves spatial resolution
- Enables inverse filtering to improve blur



Multi-frame Averaging + Filtering
(LDRI Camera)

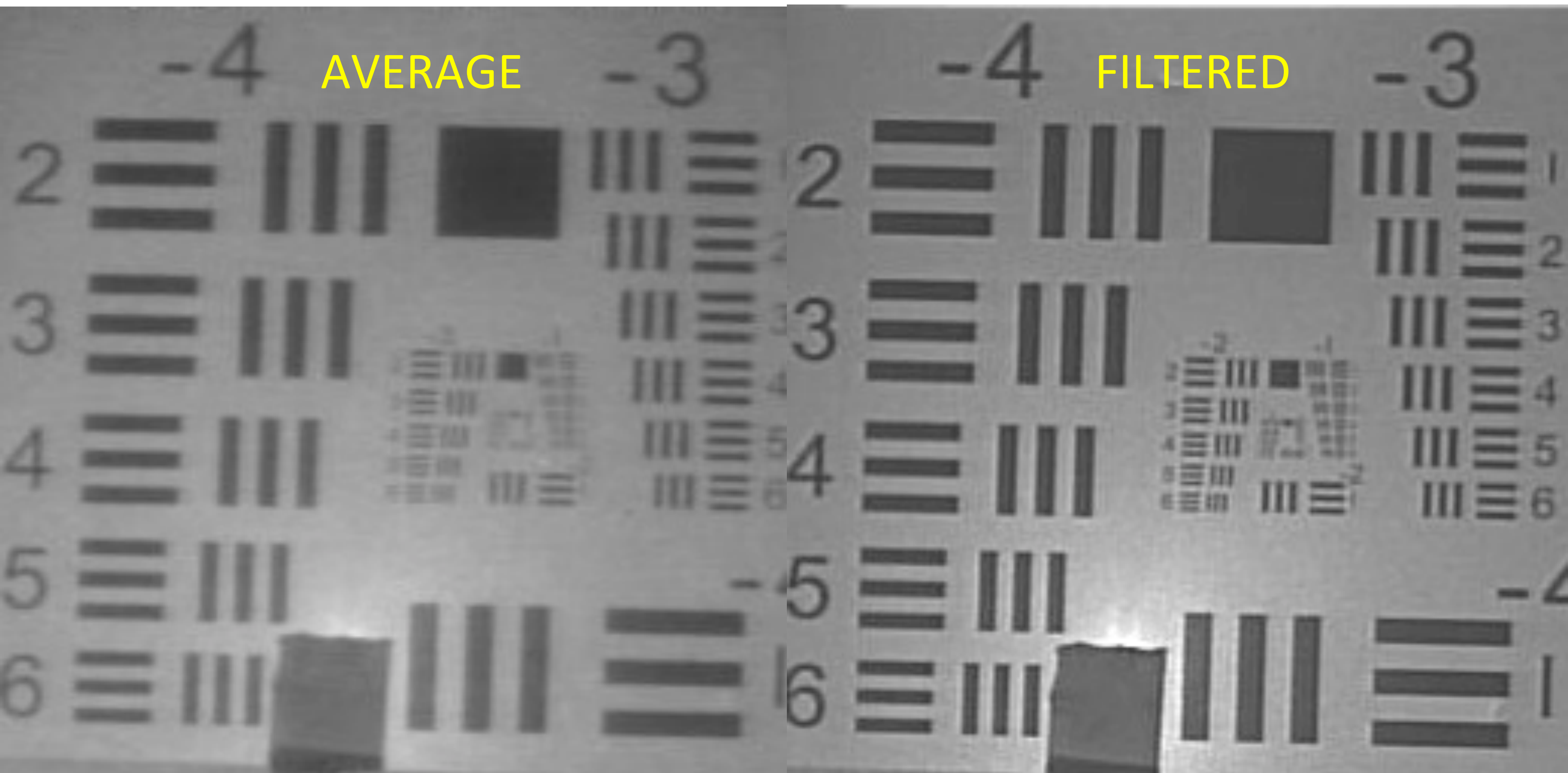
P6 Truss of the International Space Station, STS97





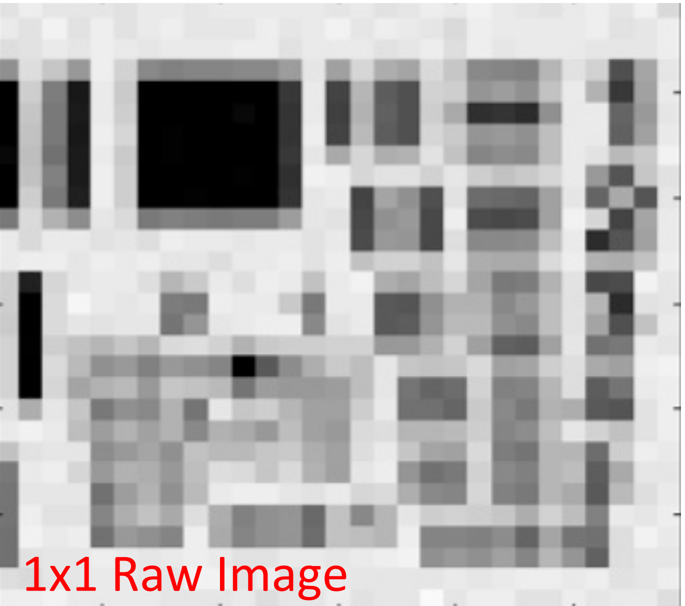
Multi-frame Averaging + Filtering
(LDRI Camera)

1951 USAF resolution up by ~26% (2 elements)

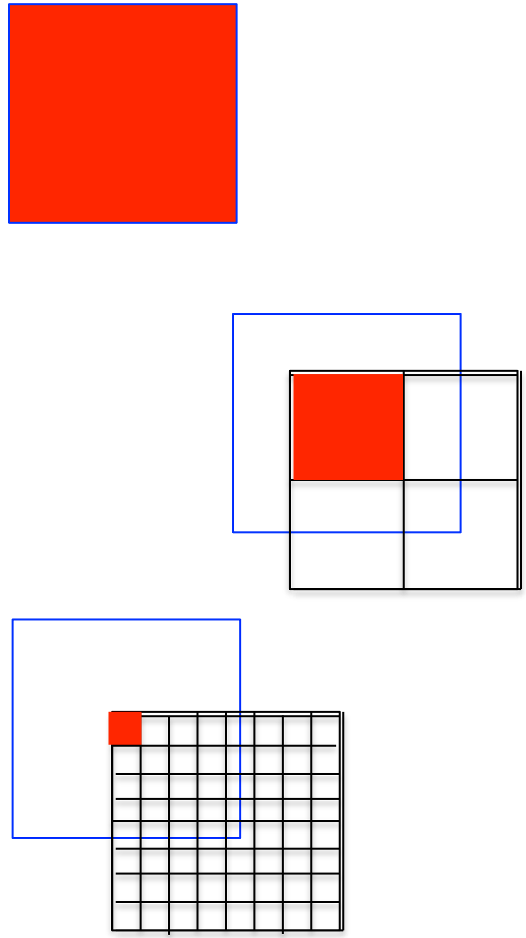


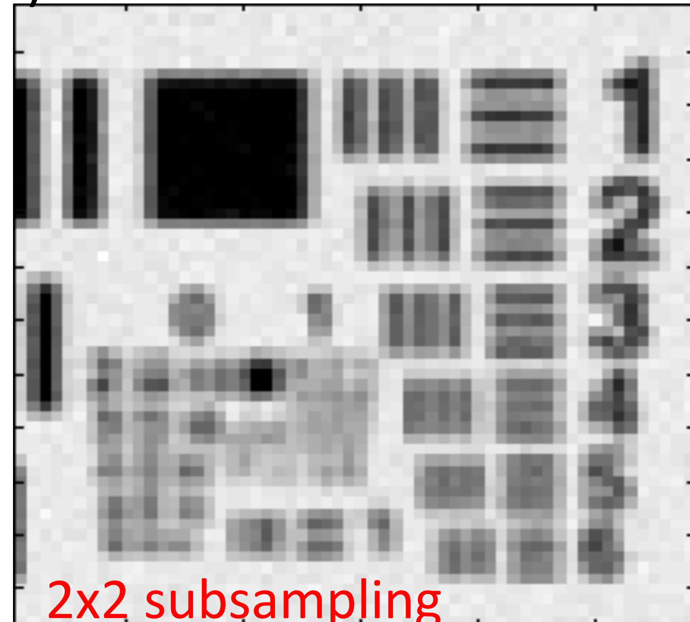
POTENTIAL OF SUPER RESOLUTION

(simulated 30x30 data)

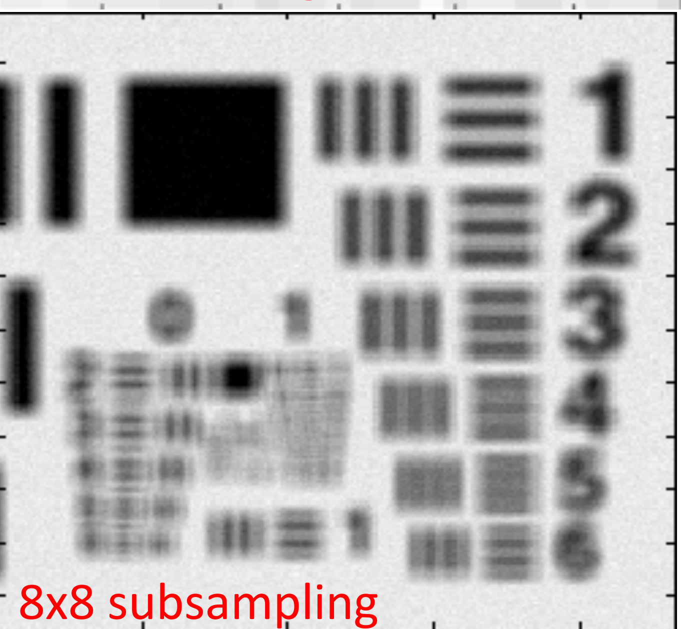


1x1 Raw Image

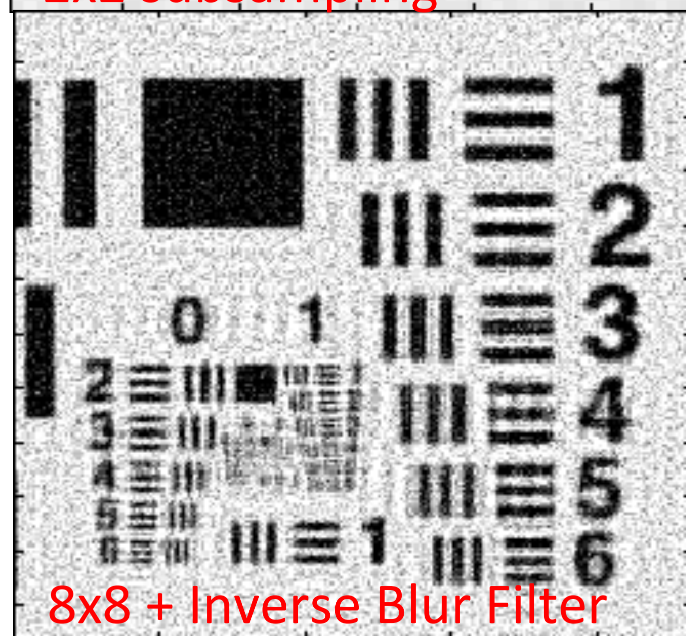




2x2 subsampling

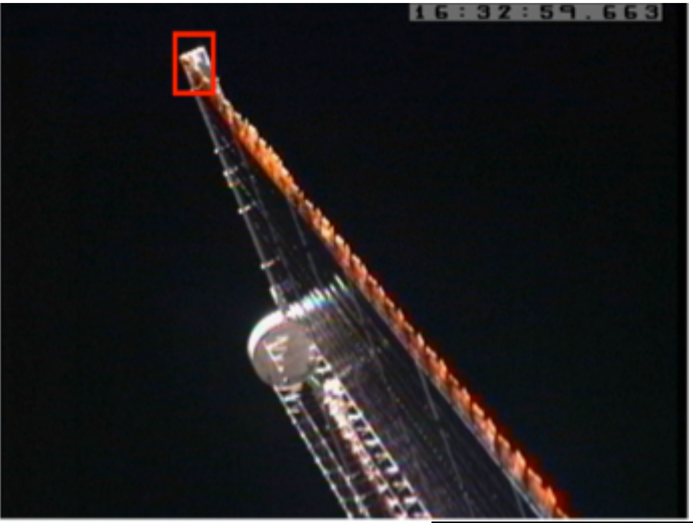


8x8 subsampling



8x8 + Inverse Blur Filter

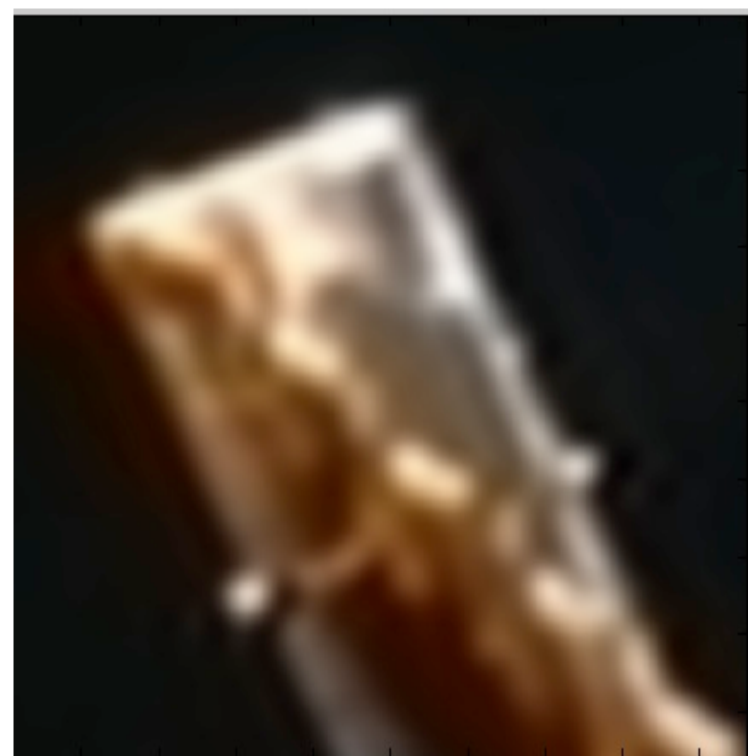
SUPER RESOLUTION OF ISS VIDEO



FULL SIZE

SINGLE FRAME

MULTIFRAME AVERAGE WITH SUBSAMPLING

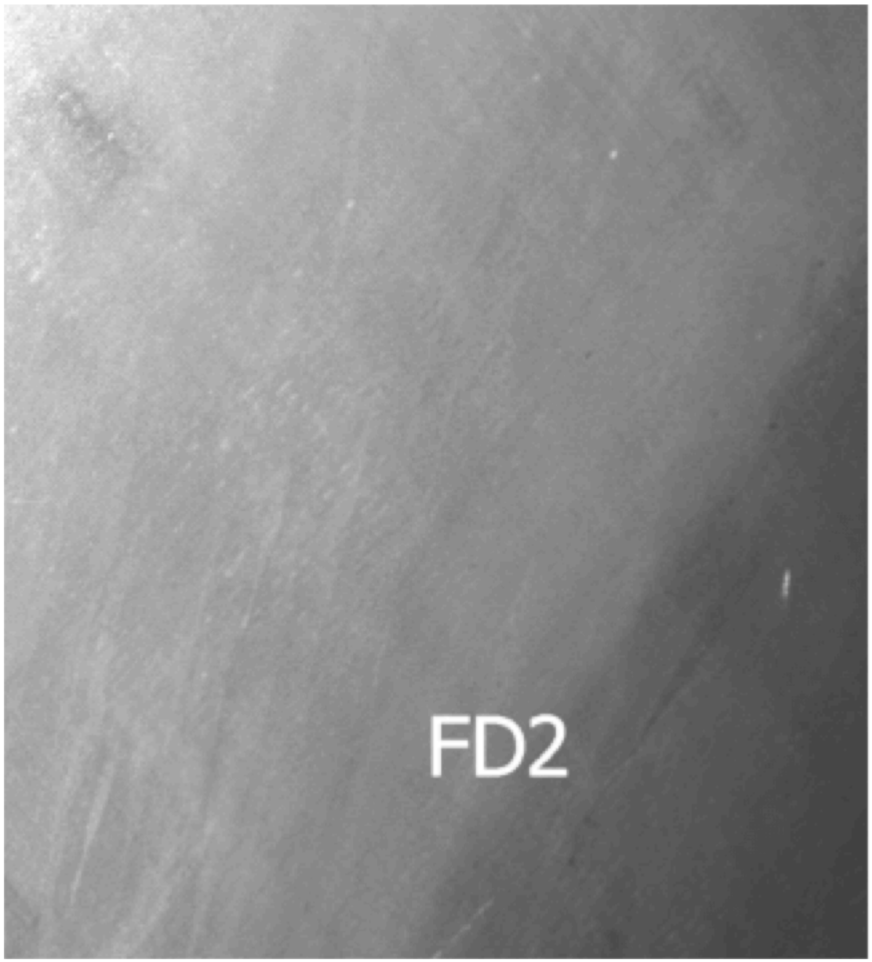


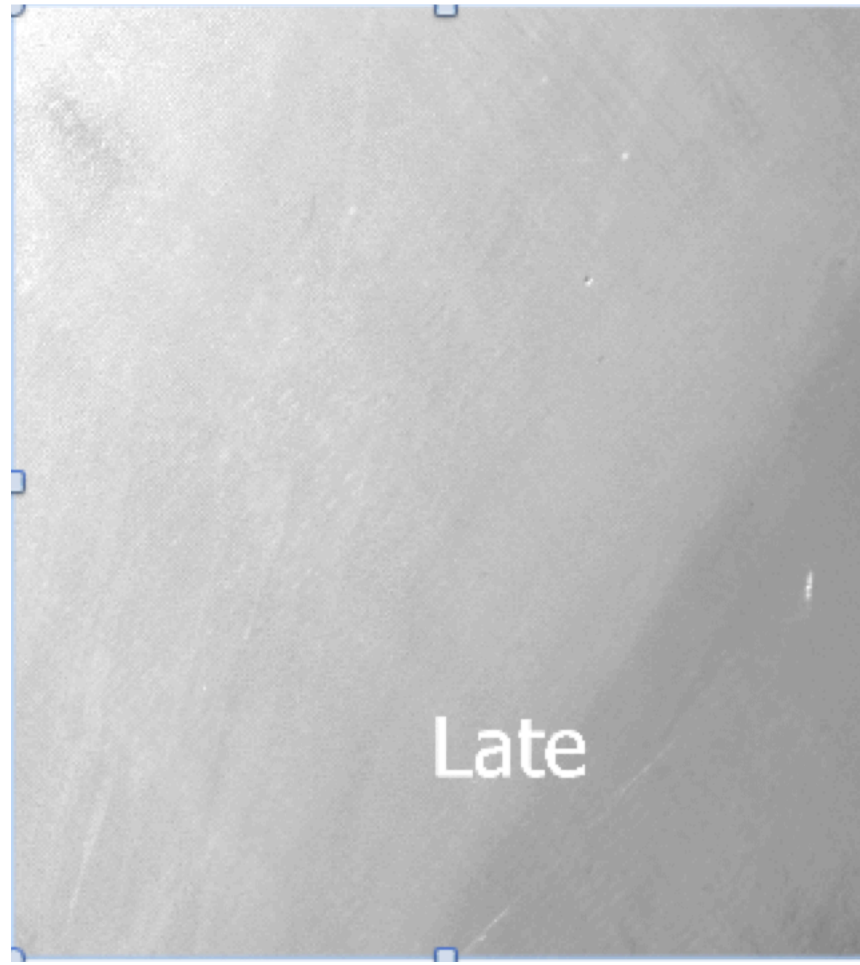
POTENTIAL OF CHANGE DETECTION (Background Subtraction)

- Sensitive to nearly invisible features
  - Light scuff marks and sub-pixel objects
  - Good results require close positioning, and minimizing lighting changes

“Blink” Change Detection

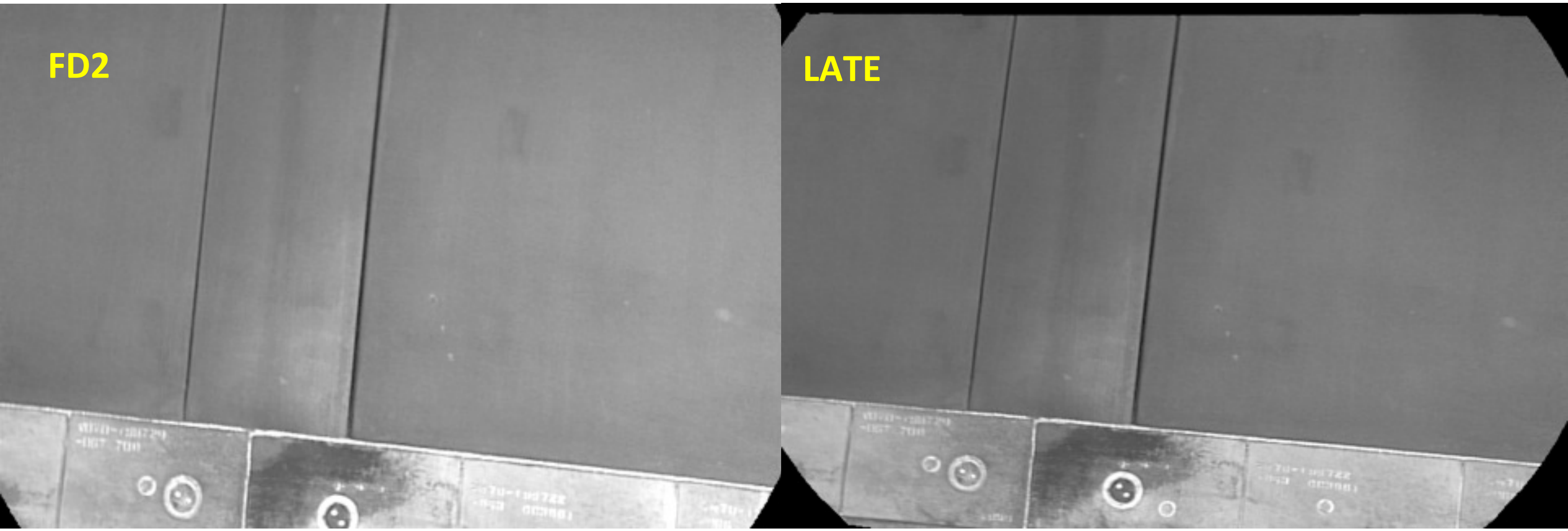
STS 130 Inspection, LDRI Camera





Change Detection

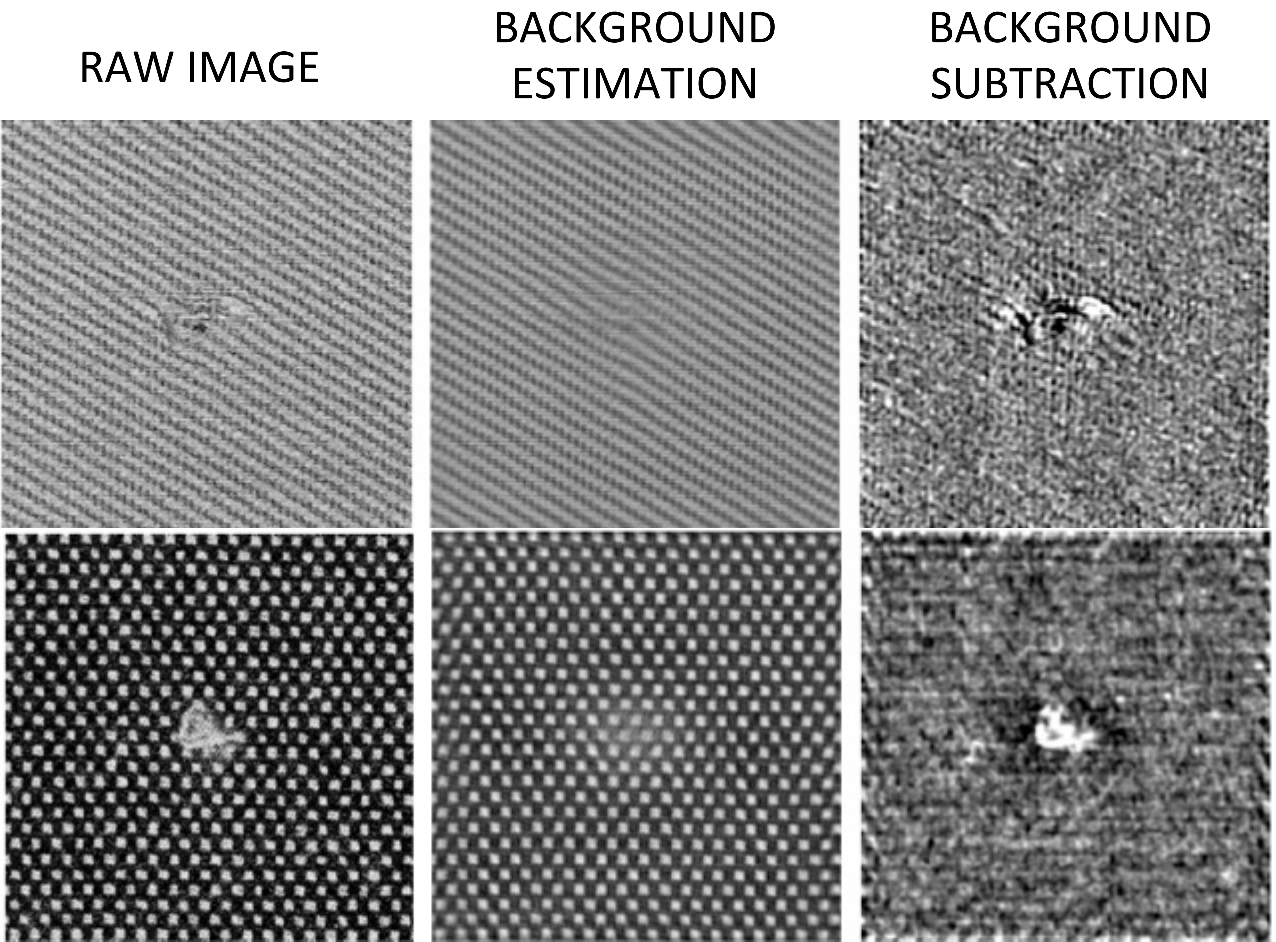
STS135 Inspection, LDRI Camera



This slide is unfinished, but will show the difference in the above images

Data-Driven Background Subtraction

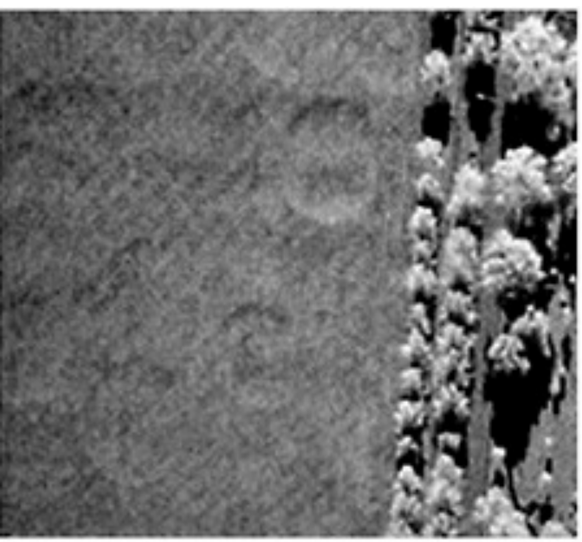
- Estimate background and subtract from image
  - Estimate background as narrow-band spectral peaks



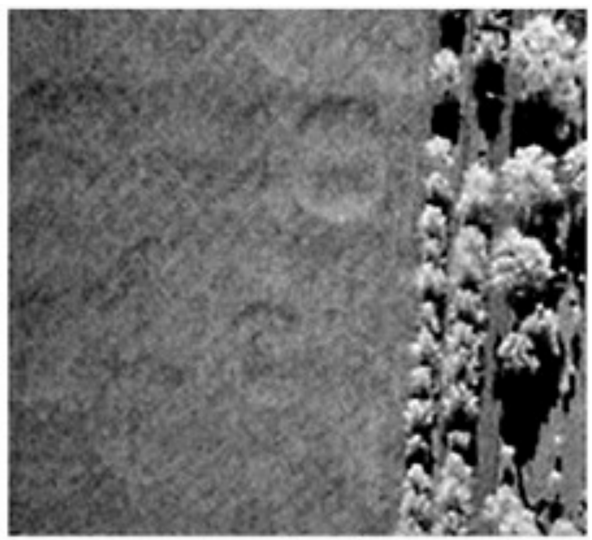
Tian, Xuwen: "Data-driven textile flaw detection methods"

Change Detection Applied to RADAR

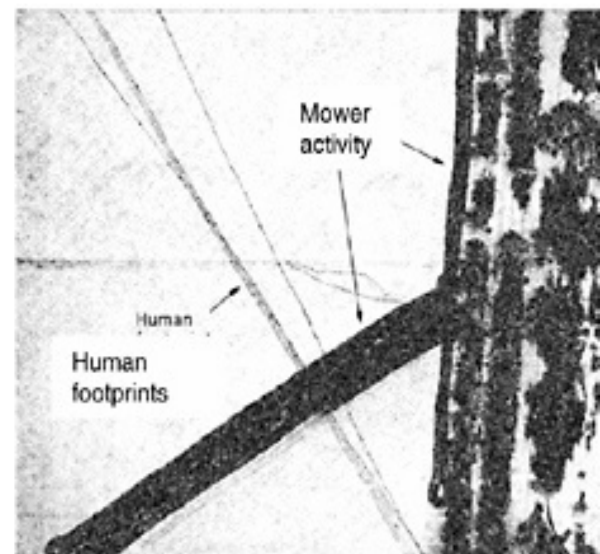
- Radars can measure complex reflectance from scene "pixels"
- Radar images (left, center) show reflectance magnitude
- CCD image (right) shows change in complex reflectance
  - Can be much more sensitive to change than magnitude
- Might this enable radar to be used for SURVEY?
  - Could sub-pixel, sub-wavelength damage be detected?



Pre-activity image



Post-activity image



CCD image

From "C4ISR for Future Naval Strike Groups", NRC, 2006

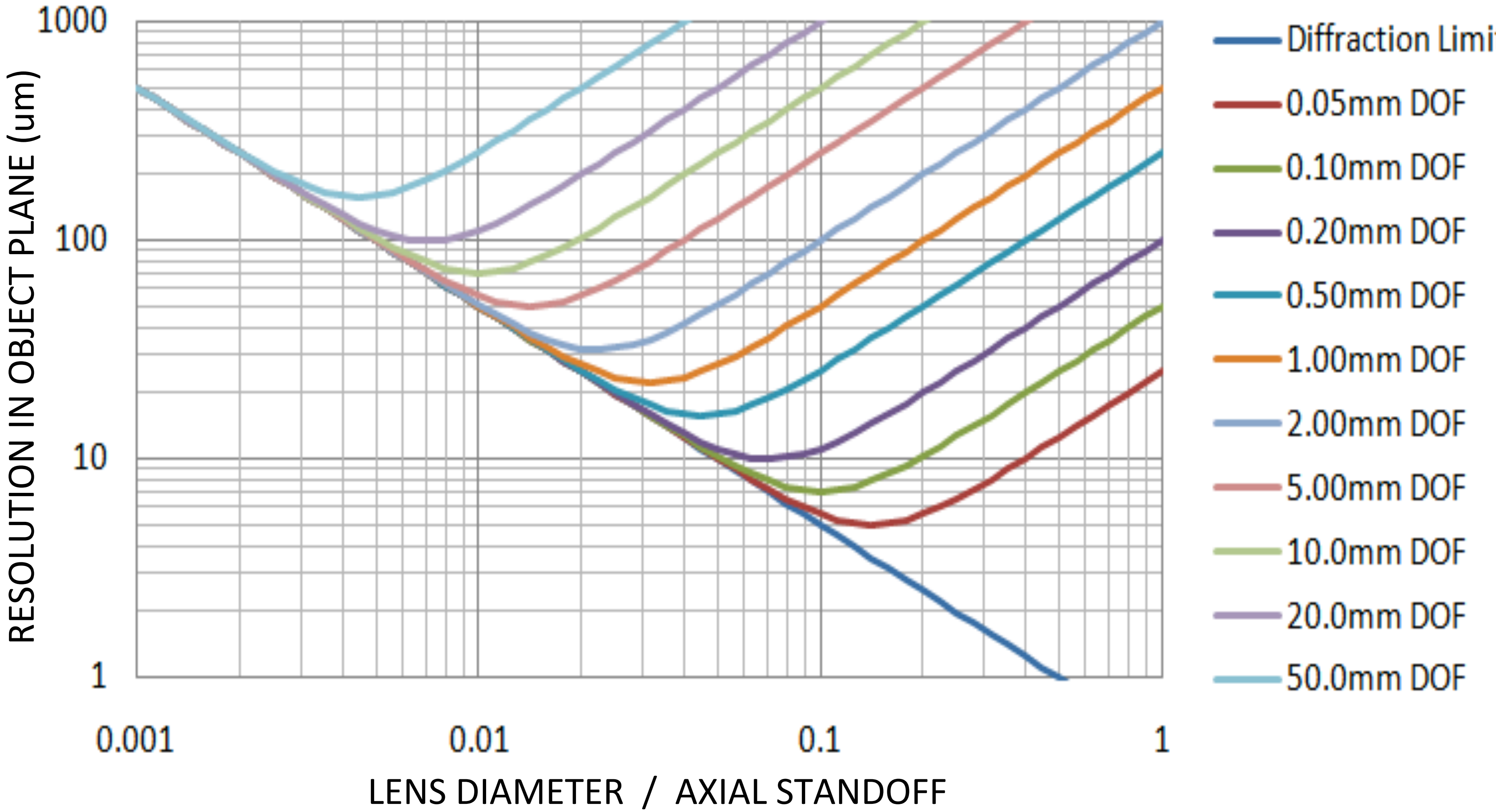
Application 2: FOCUSED INSPECTION
Measure Damage Size and Depth

Camera Suitability

- Incentive to use Cameras
  - Existing resource, robotic flexibility
  - High resolution, visual context
- Issues with Cameras
  - Depth measurement required
  - Non-penetrating, limited to line-of-sight
  - Illumination difficulty into narrow openings
  - Tradeoff between Resolution and Depth of focus

RESOLUTION VS. DEPTH OF FOCUS

(500nm Wavelength)

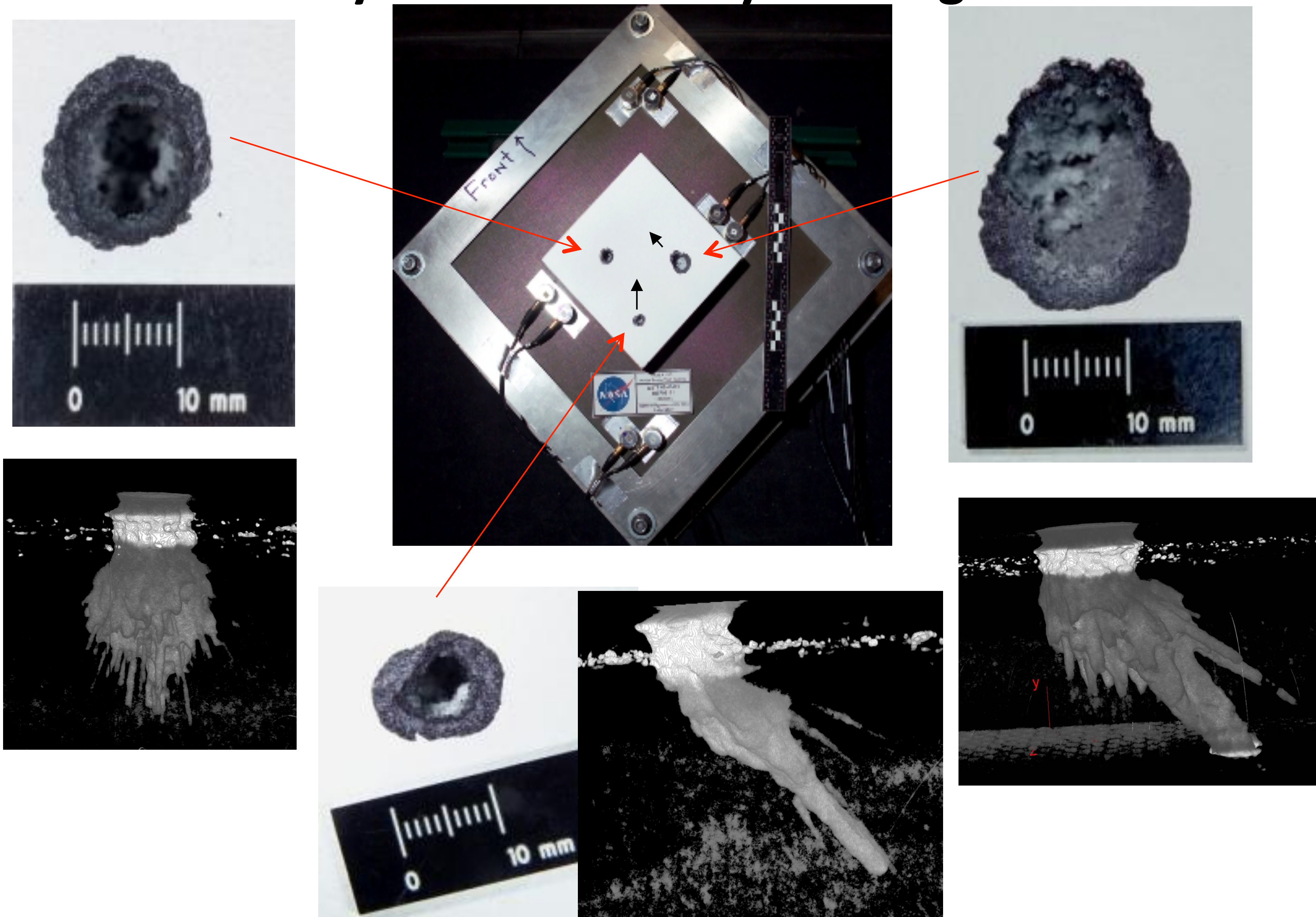


Examples Yielding 100um Resolution, 20mm DOF

(FOCAL LENGTH AS REQUIRED)

- 50mm (2”) Standoff: 0.25-0.50mm Lens Diameter
  - “Borescope” type of camera
  - Requires special prox ops approval
- 500mm (20”) Standoff: 2.5-5.0mm Lens Diameter
  - Nikon or video camera at high F/#, small telephoto lens
  - Dextre prox ops
- 1m (3.1’) Standoff: 5.0-10mm Lens Diameter
  - SSRMS prox ops
- 10m (16’) Standoff: 50-100mm Lens Diameter
  - Nikon or video camera at low F/#, large telephoto lens

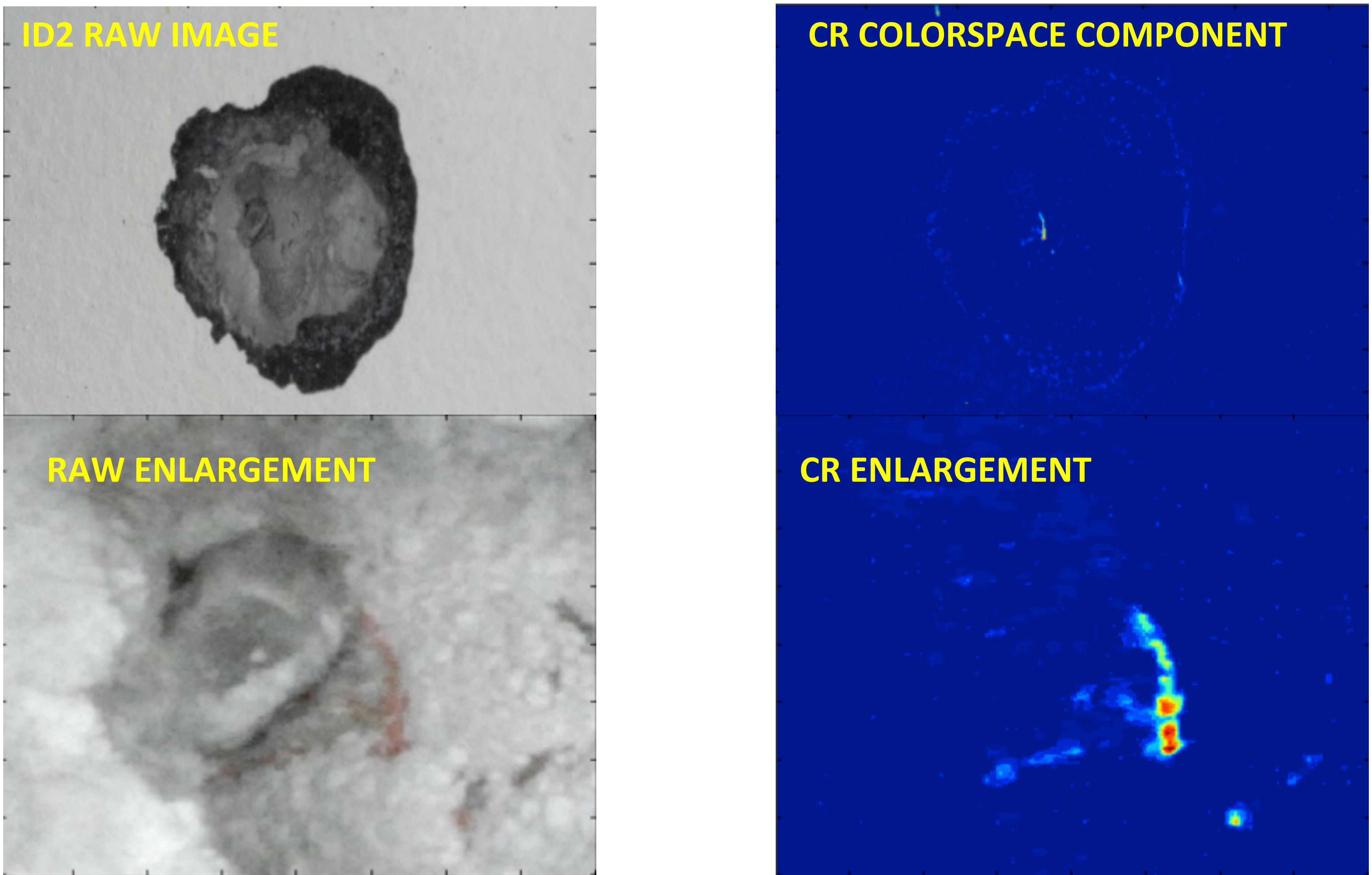
Hypervelocity Impacts to Sample Silica Re-entry Tile (#3) Entry Holes and X-ray CT Images



(Courtesy NASA/KX)

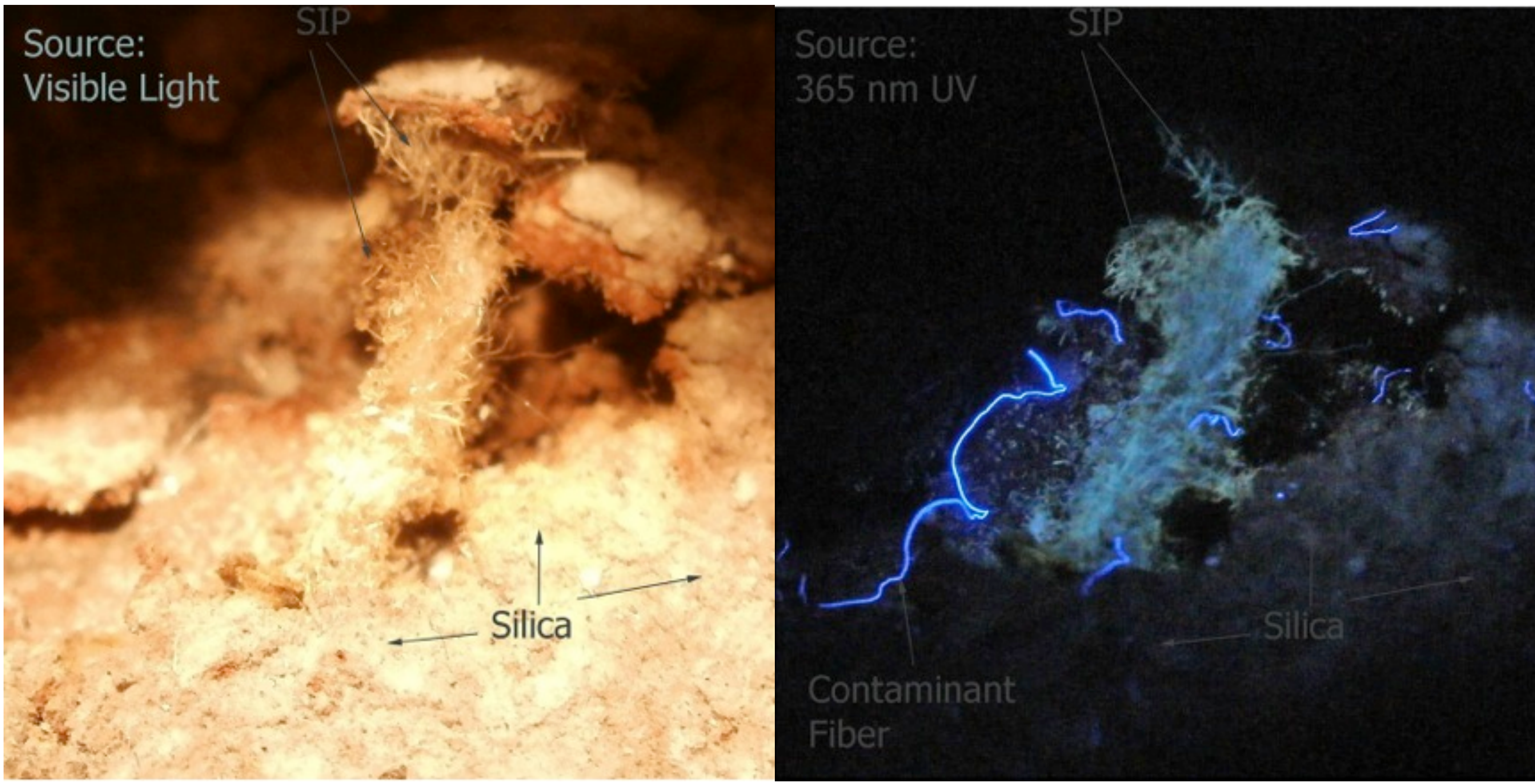
COLORIMETRY (Nikon Camera)

- Color in a critical layer can be a sensitive damage indication
- In this case, the critical layer is colored red



FLUORESCENCE

- The critical damage site may not always be visible
- Fluorescent material from a critical layer can be a sensitive indicator in the visible debris



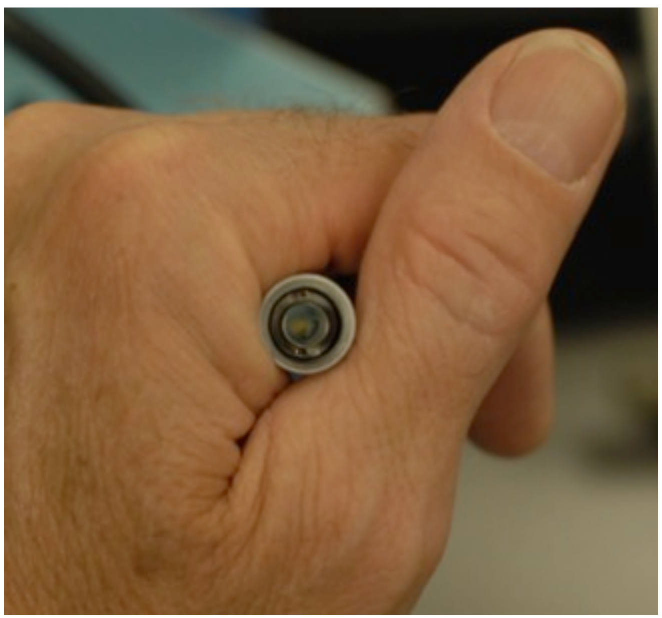
(Source: Michael Rollins, JSC Image Sciences)

3D Evaluation

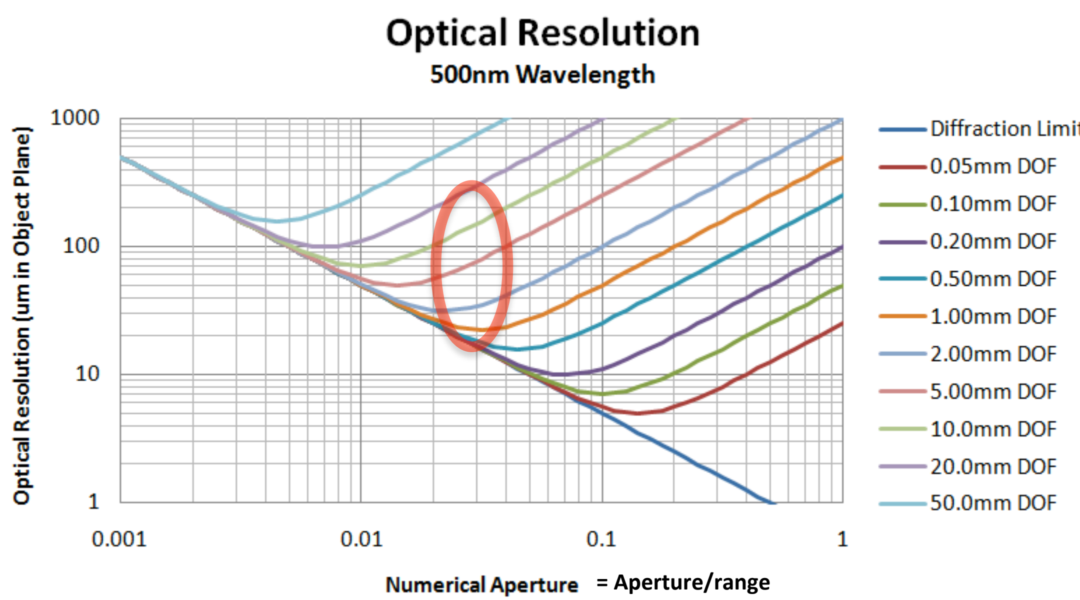
- Goal: Measure size and depth of ID1, ID2, ID3
- Data Base: 2-D camera images, multiple poses
  - Borescope Camera (~1" standoff)
  - Nikon Camera (~20" standoff)
- Depth determination
  - Using parallax: "Structure From Motion"
  - Using focus: "Structure from Focus"

Borescope Testing

Borescope Configuration. Pulnix camera (at right) is optically coupled to distal end of 8-mm borescope (at left). Illumination is coupled through flexible light guide (at center).



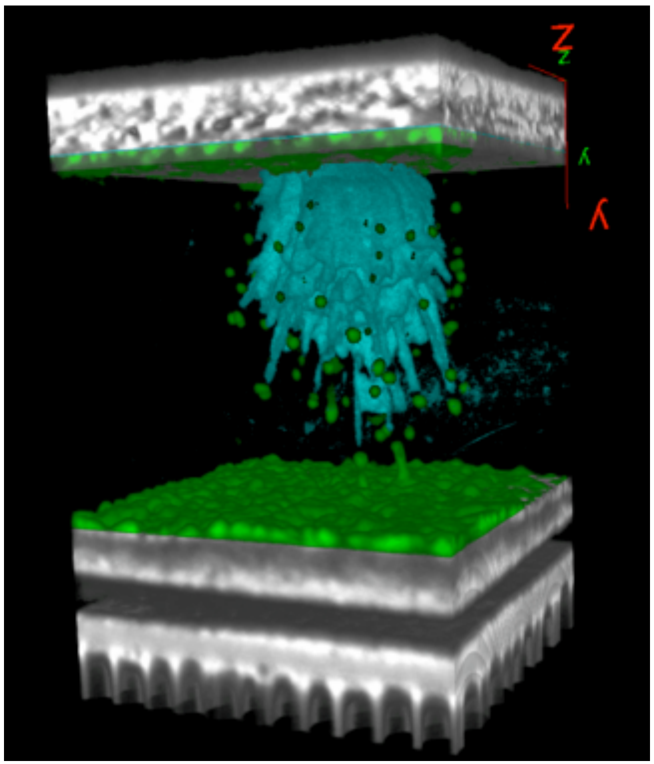
Illumination ring surrounding input window



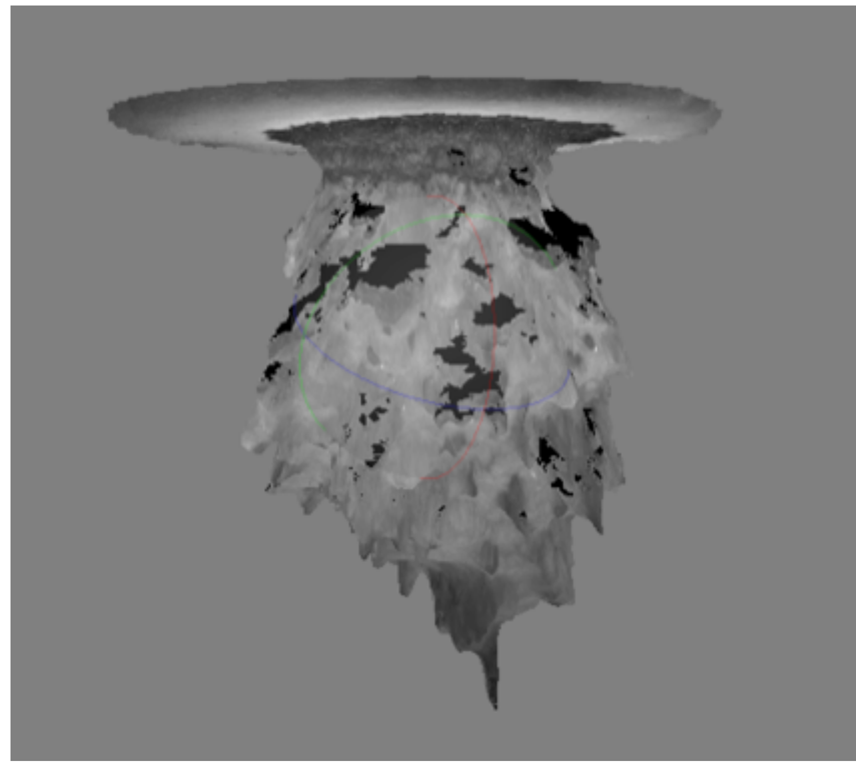
= 20-40mm range, 1mm aperture, 60° FOV

ID1 Structure From Motion

- 20mm normal standoff
- Center, 4mm up, down, left, right



TRUTH DATA
(Studor/Olstad/Smith/Rollins: "MMOD Inspection and Detection Study and Recommendations")

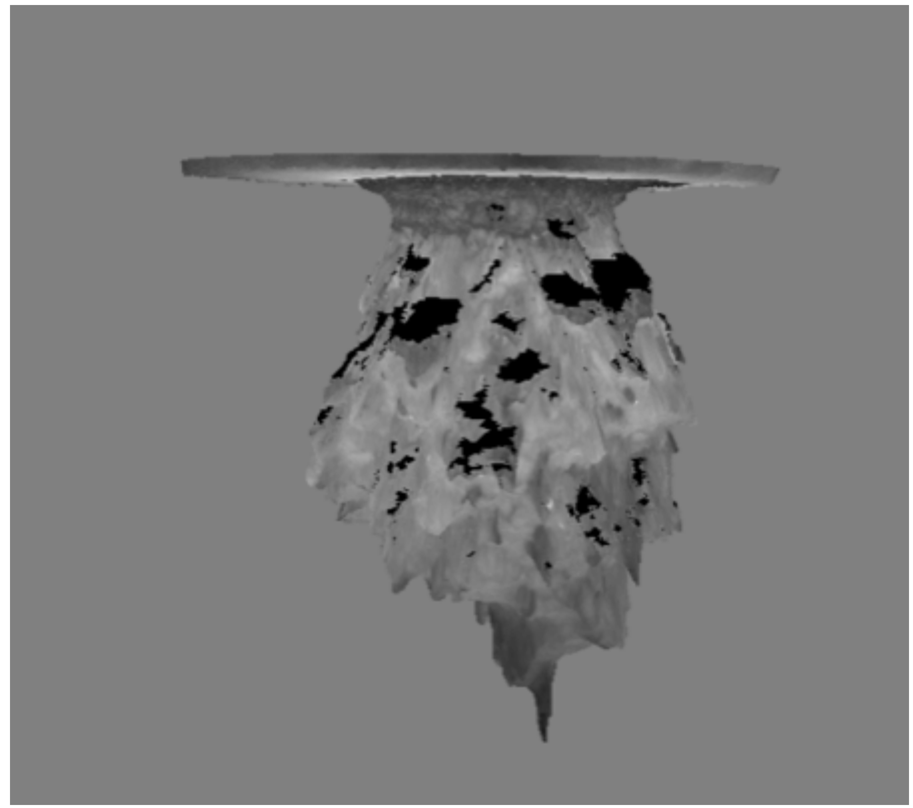


BORESCOPE SFM DATA
(PhotoScan software analysis)

ID1 Structure From Motion

- 20mm normal standoff
- Center, 4mm up, down, left, right

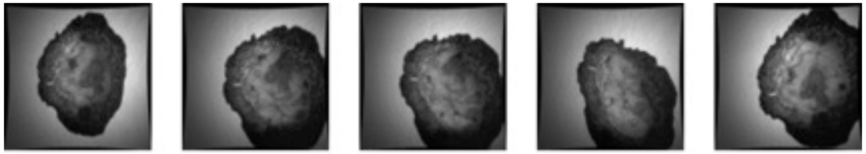
TRUTH DATA
(Courtesy Michael Rollins, JSC Image Sciences)

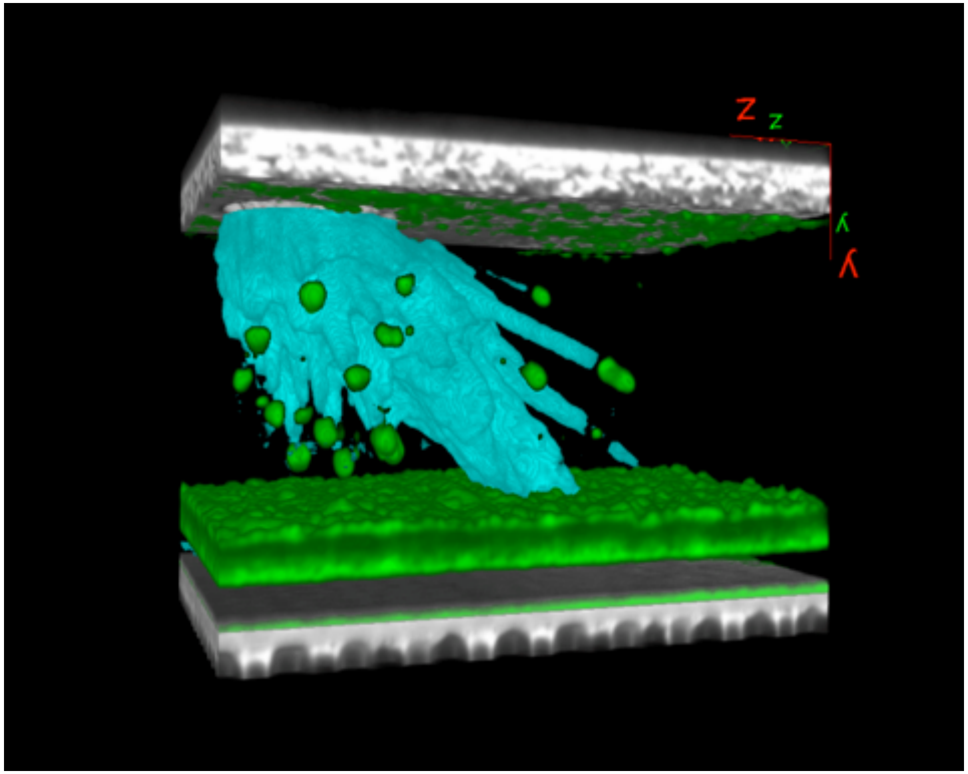


BORESCOPE SFM DATA
(PhotoScan software analysis)

ID2 Structure From Motion

- 17-23mm axial standoff
- Conical scans at 30,40,50°
- 10° azimuth steps





TRUTH DATA
(Studor/Olstad/Smith/Rollins: "MMOD Inspection and Detection Study and Recommendations")

BORESCOPE DATA RECONSTRUCTION
(PhotoScan software analysis)

ID2 Structure From Motion

- 17-23mm axial standoff
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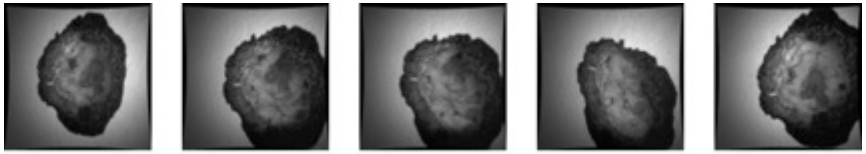
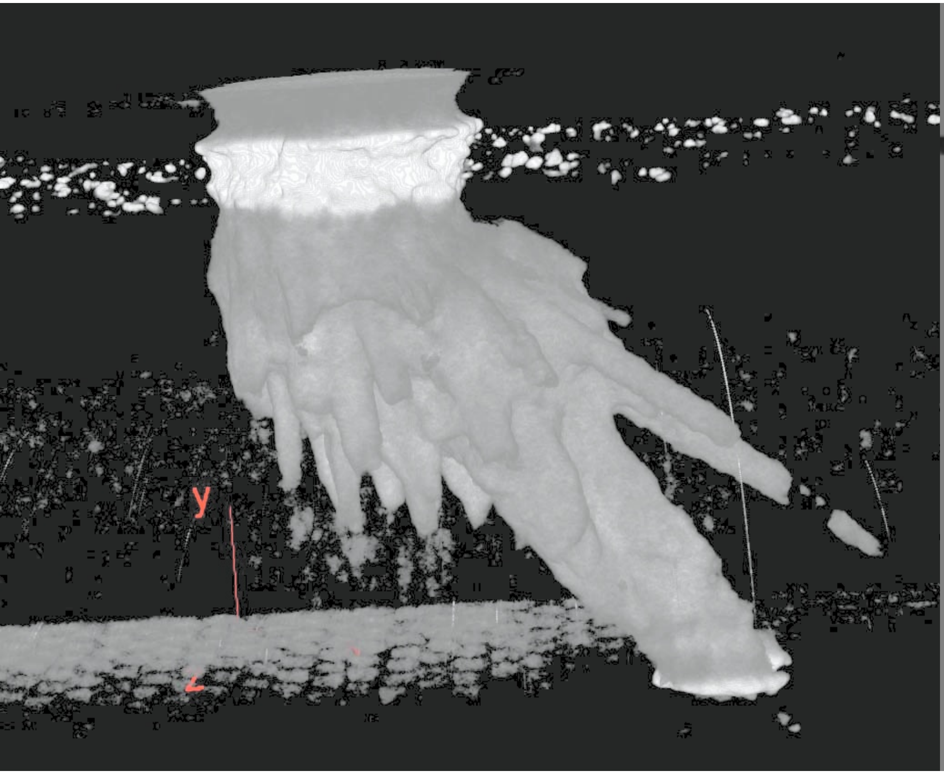


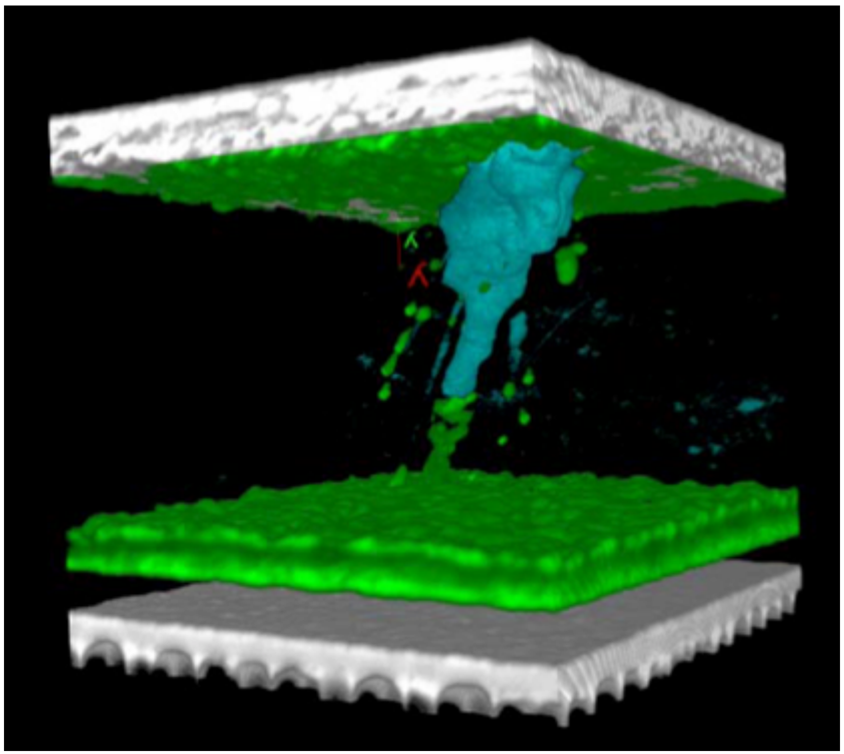


TRUTH DATA
(Courtesy Michael Rollins, JSC Image Sciences)

BORESCOPE DATA RECONSTRUCTION
(PhotoScan software analysis)

ID3 Structure From Motion

- 8-10mm axial standoff
- Conical scans at 30, 40°
- 10° azimuth steps



TRUTH DATA
(Studor/Olstad/Smith/Rollins: "MMOD Inspection and Detection Study and Recommendations")

BORESCOPE DATA
(PhotoScan software analysis)

ID3 Structure From Motion

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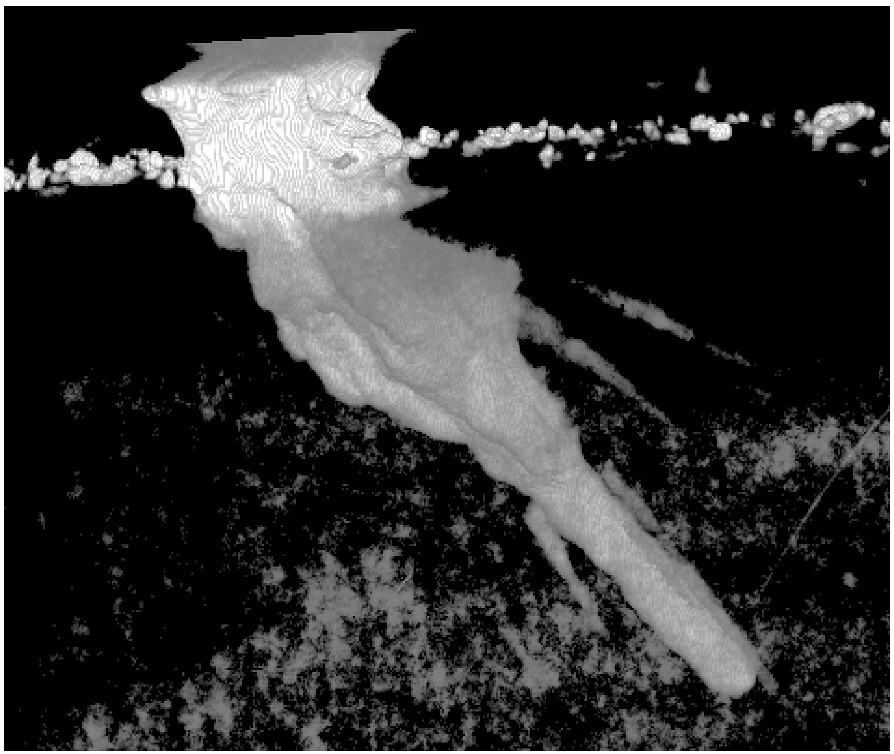

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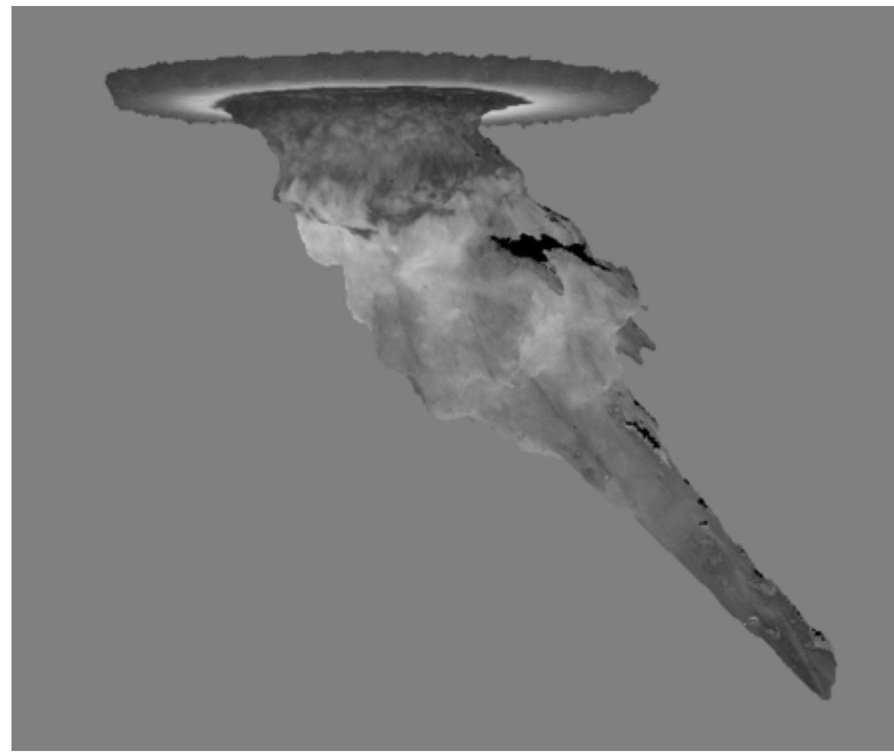
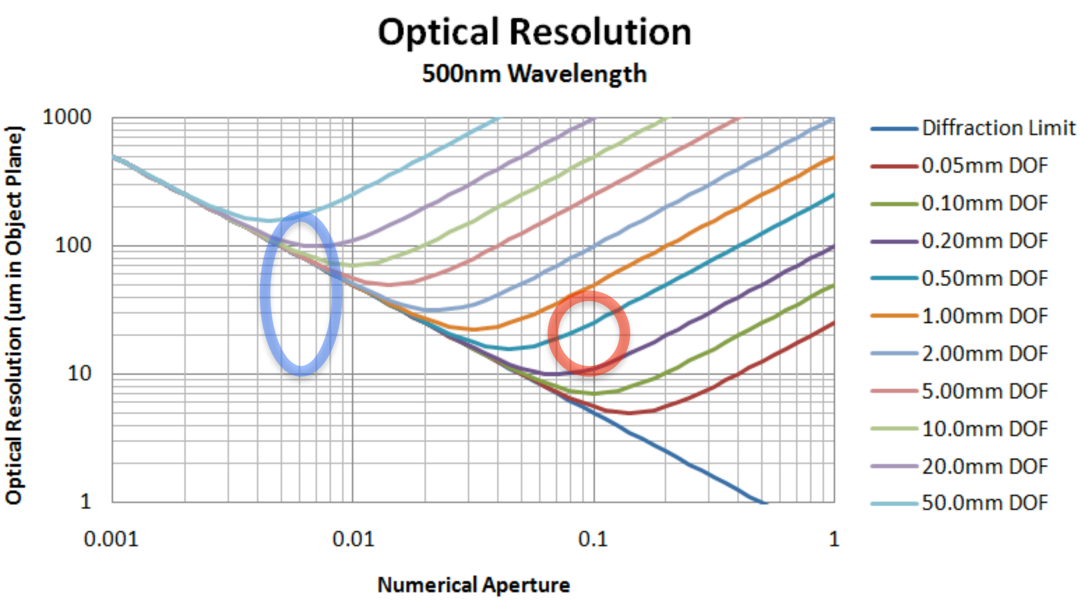


BORESCOPE DATA
(PhotoScan software analysis)

Nikon Testing

Nikon DX2s camera with Micro-Nikkor 105mm f/2.8 lens and ring illuminator (at right) viewing AETB-8 target mounted on computer-controlled, translation and rotation stage (left).

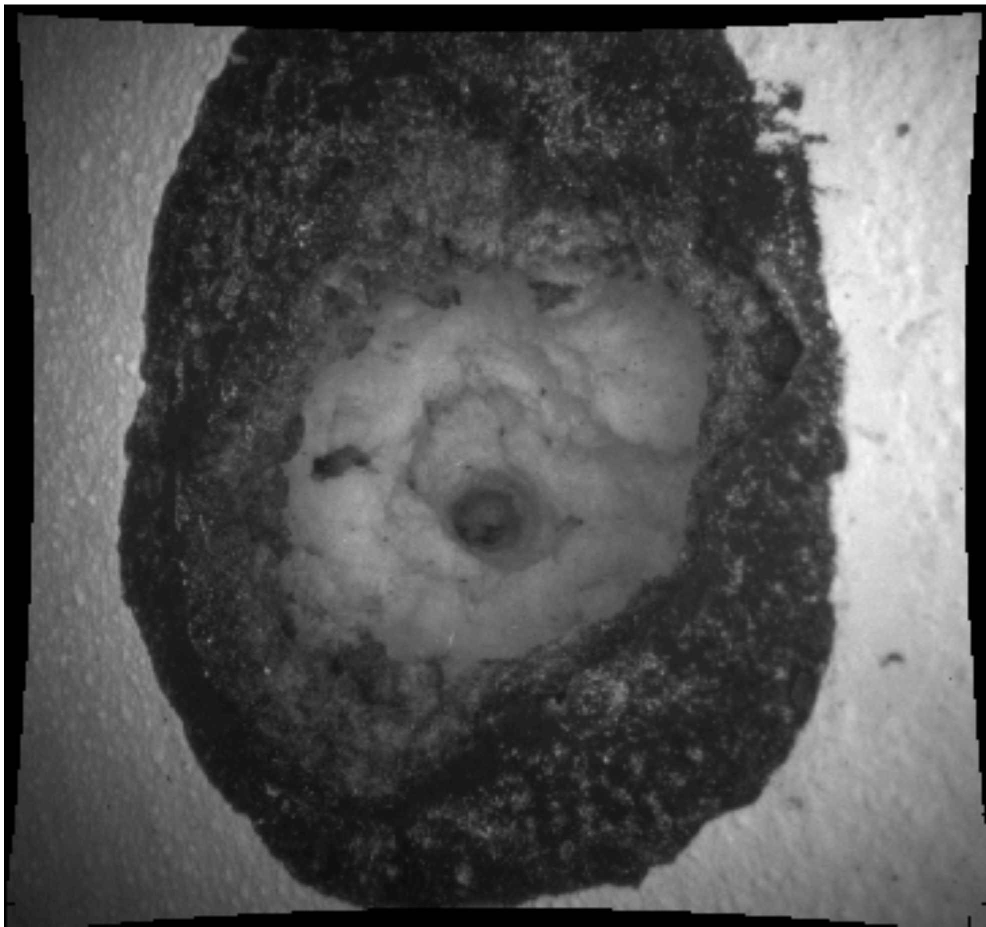


= 300-500mm range, 37 mm aperture, 5.5um pixels

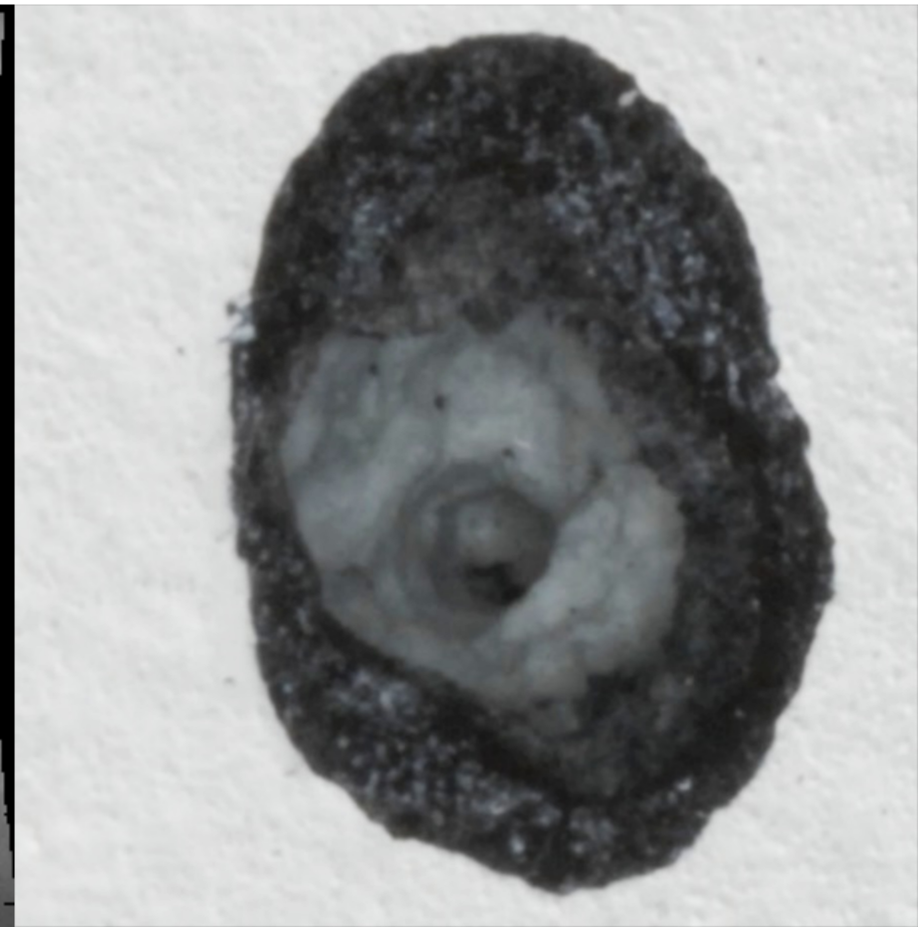
= 500mm range, 3 mm aperture, 5.5um pixels (4-pixel blur)

Borescope vs Nikon Comparison

BORESCOPE FROM 10mm (0.4”)



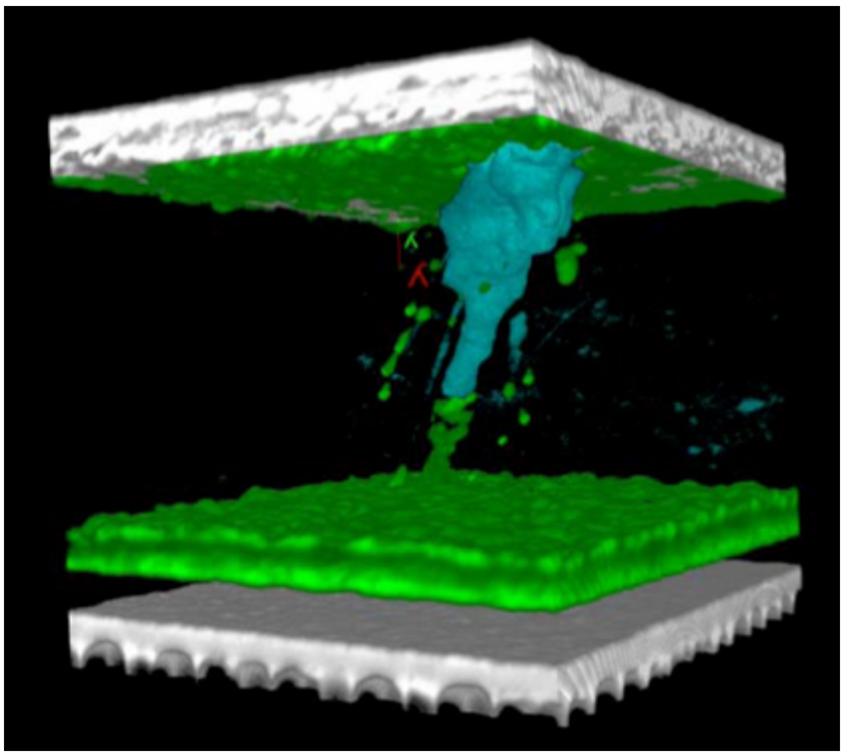
NIKON FROM 0.44m (17.3”)



ID3 Structure From Motion

(Nikon Dataset Limited to just 5 views)

- 266mm (17.3") axial standoff
- 45° incidence
- 5 images at 20mm steps



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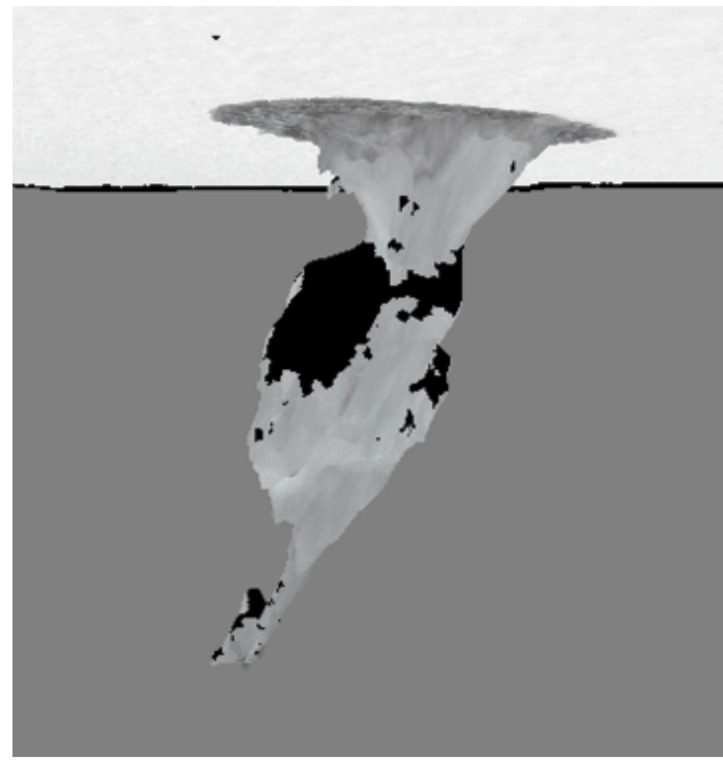

NIKON DATA
(PhotoScan software analysis)

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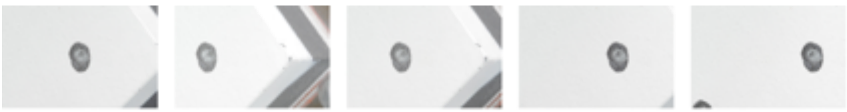

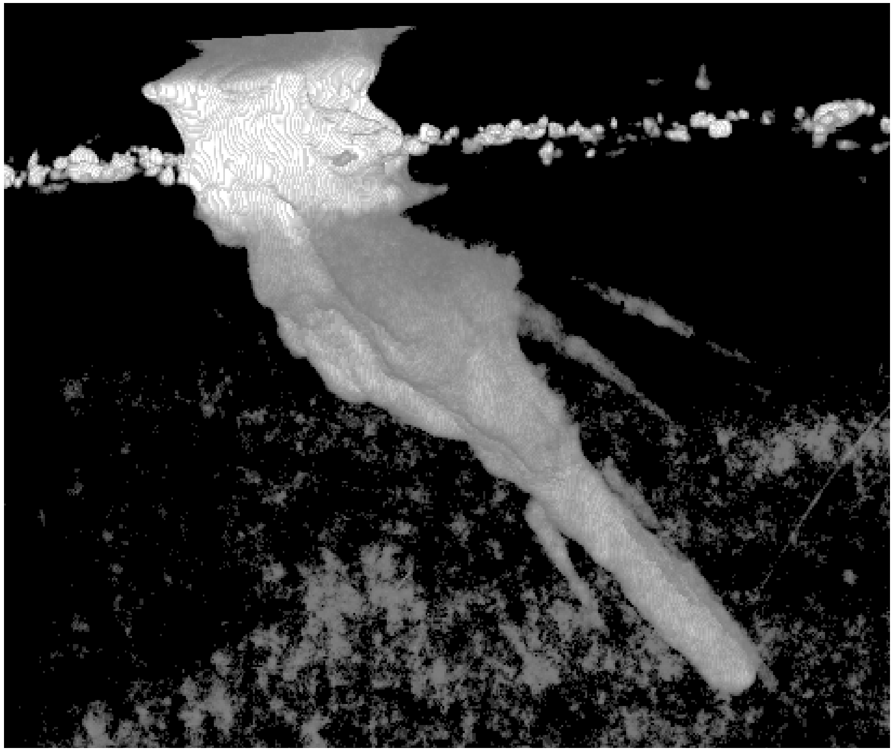

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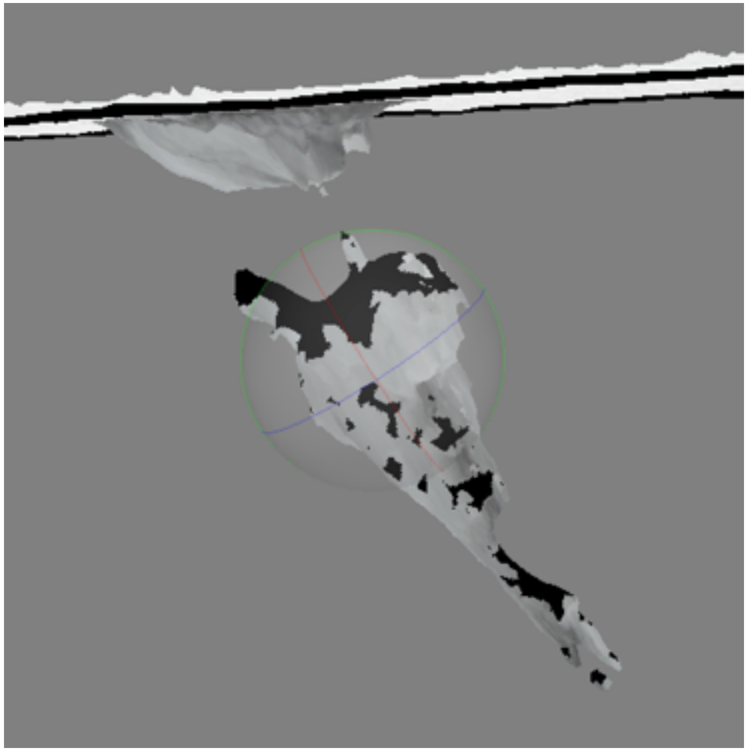
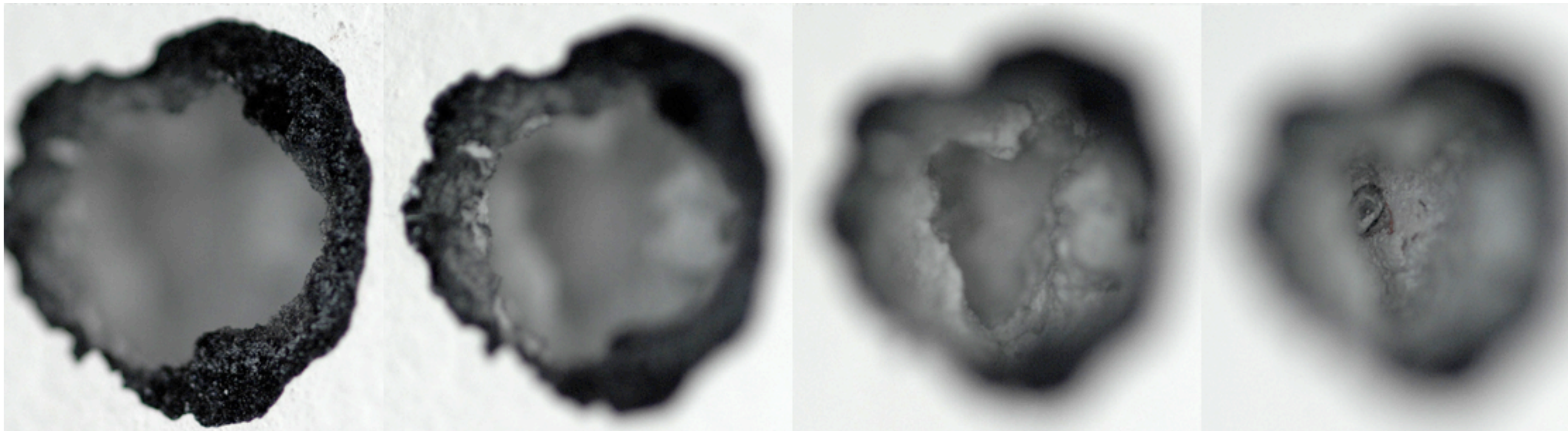
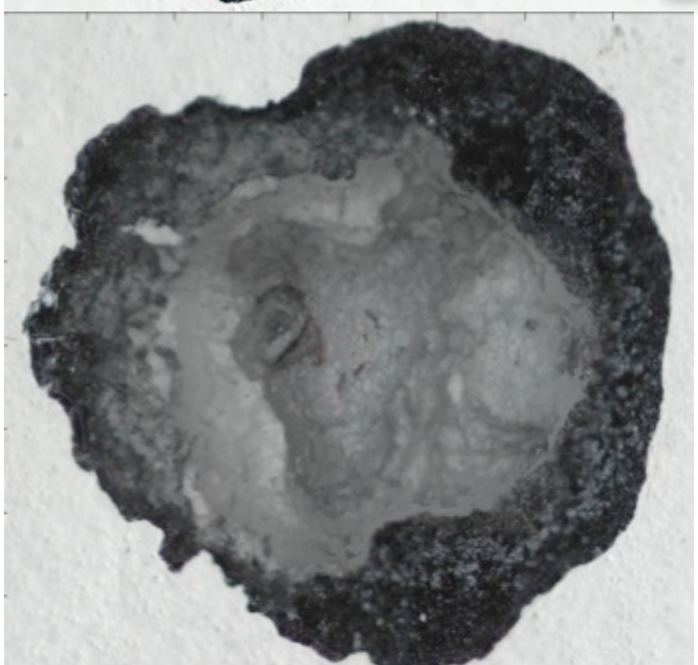
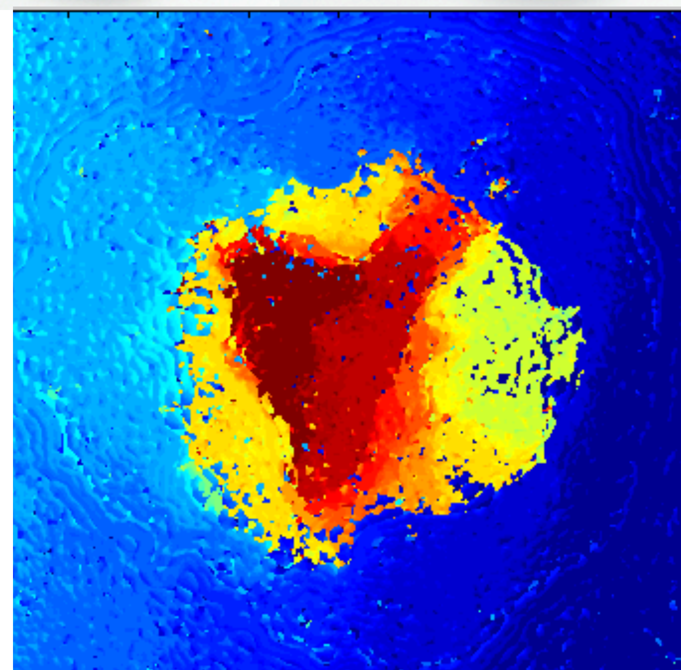


NIKON DATA
(PhotoScan software analysis)

STRUCTURE FROM FOCUS







3D from 2D Conclusions

- Proper illumination and lens are crucial
- Over-the-counter Structure From Motion software performs well
  - Further validation needed
    - More examples, difficult cases
    - Scaling and dimensional comparisons with truth
  - Structure from Focus also appears feasible
    - Was investigated in less detail
    - May complement SFM
- Potential improvement by combining focus, motion algorithms
  - Results presented here use either but not both simultaneously
- Best results require many views
  - Easily configured using robotics
  - Could be performed with either video or Nikon
  - Processing in near-real time
    - ~10min on laptop
    - Estimated 30s on high performance desktop

RADAR Observations

- Lower frequencies penetrate better
- Return from reflective backing preferred to direct return
- Circular polarization preferred to linear/none
- Polarization ratio preferred to magnitude of either polarized or unpolarized return

“Insitu Damage Imaging of Inflatable Structures”
Studor, Madaras, Nellums, McMakin

NASA test article

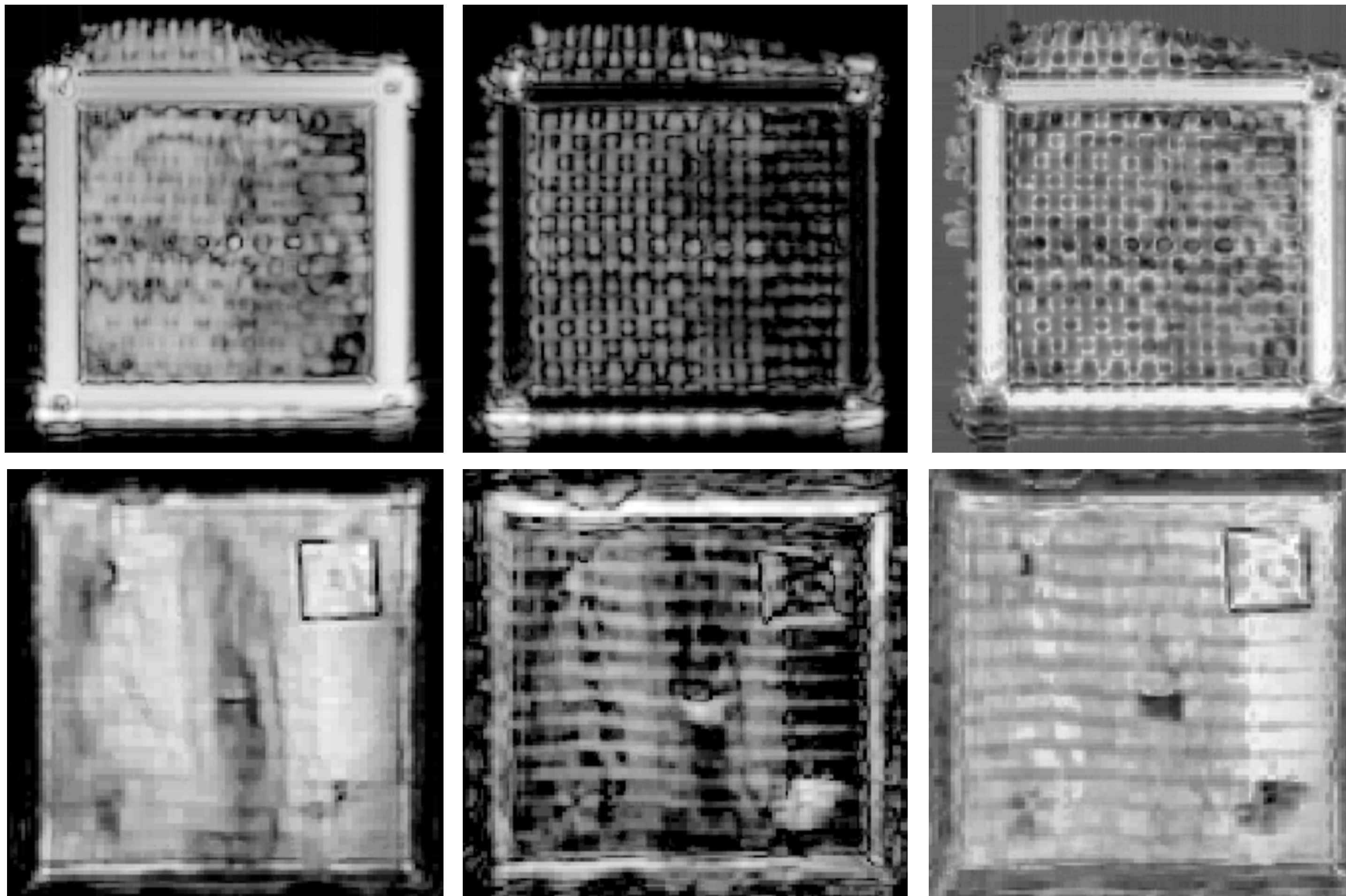
10-20 GHz Radar, Circularly Polarized

(Courtesy Douglas McMakin, PNNL)

R-L | R-R | R-L / R-R

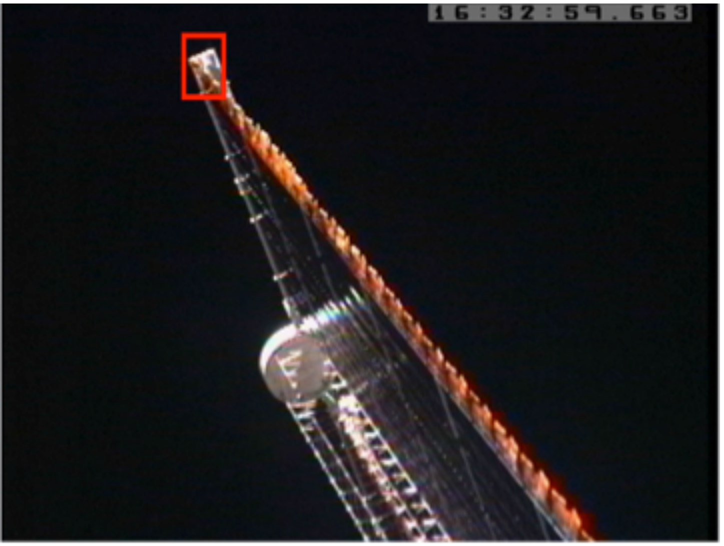
Direct Return from Undamaged Surface

Reflected Return from MLI Backing



APPLICATION 3: VIBROMETRY

Identify modes to validate codes and detect changes



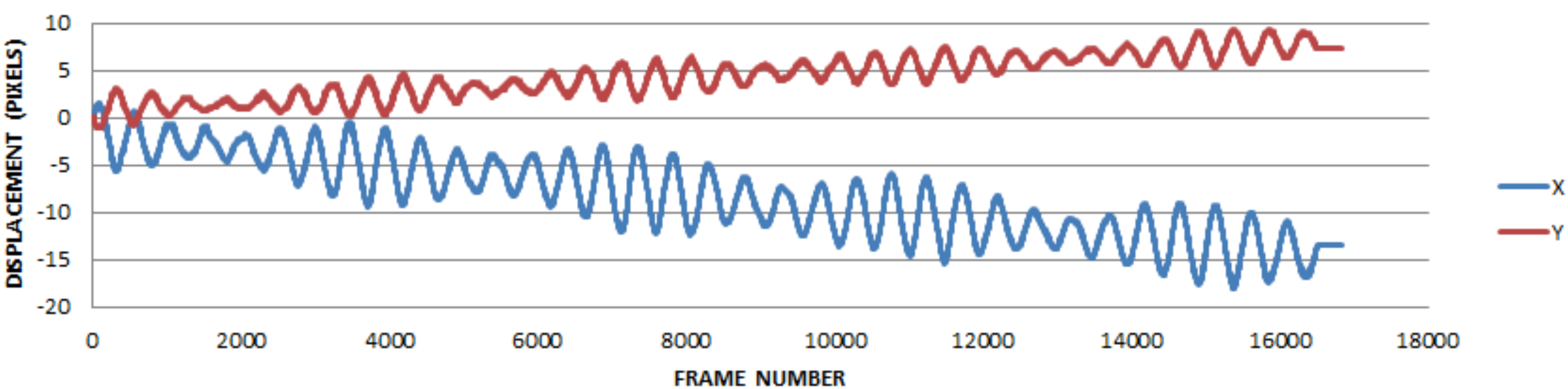
Approach:

Adjust each video frame, using a motion model, to best match a reference image.

Key Need:

Adequately identify more modes

DX,DY Displacement, Blanket Box of S43A-SAW, Frames 0-16828



("Response of ISS S4-3A Solar Array Wing to Reboost 6/17/2011" , courtesy Donn Liddle, NASA/JSC Image Sciences)

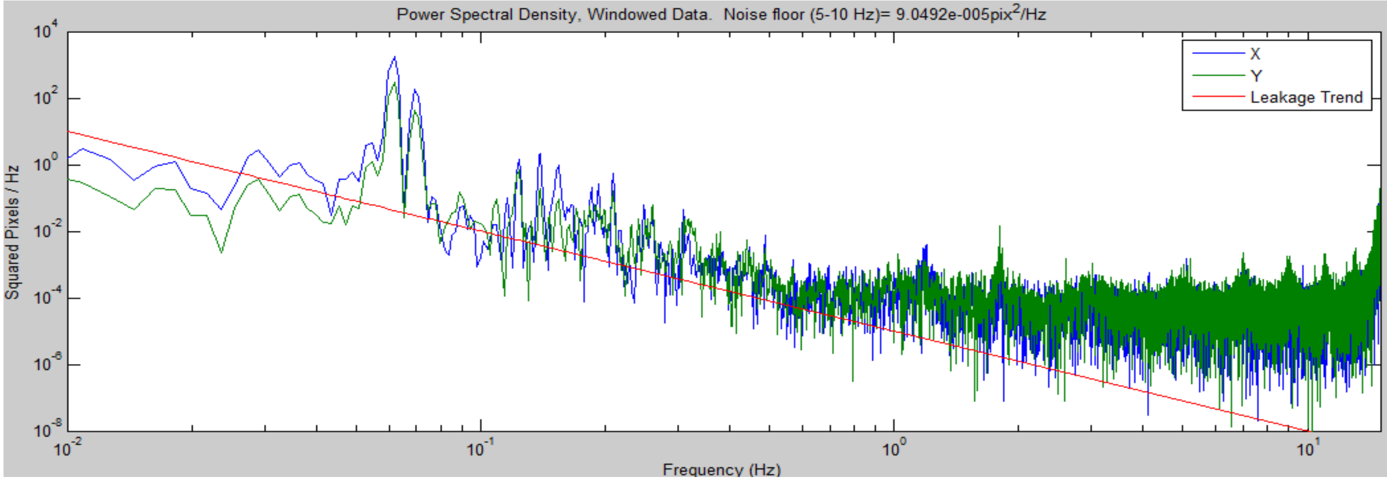
VIBROMETRY CONCLUSIONS Potential Areas for Improvement

- Registration Algorithm
  - Especially regarding motion interpolation
- Video Error Correction
  - Many systematic issues with downlinked video
- Motion Model Degrees of Freedom
  - Current model is offset only
- Reference Image Accuracy and Resolution
  - Effect of aliasing and desire for super-resolution

Spectral Comparison of Results

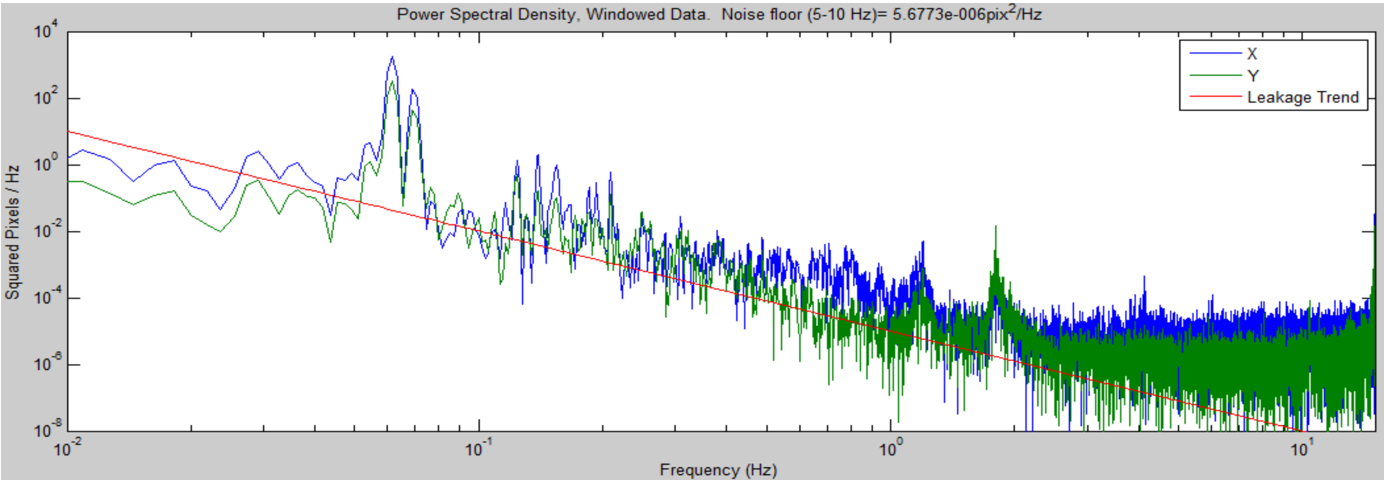
Spectrum of Existing Analysis

(floor =0.01 pixels/root-Hz)



Spectrum of Refined Analysis

(floor =.0024 pixels/root-Hz)



END