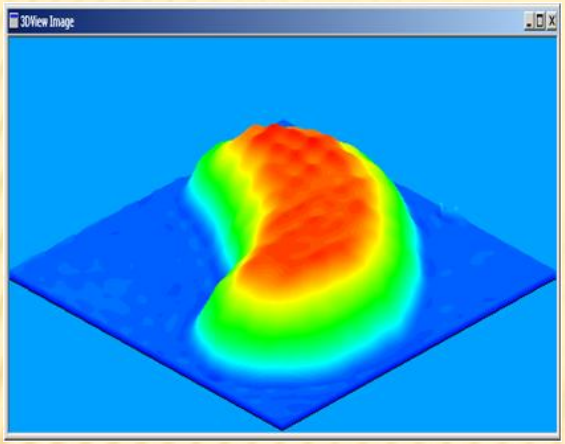
# Fourier Transform Profilometry (FTP) for Mapping Tank Residuals

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May 20, 2009

# Agenda

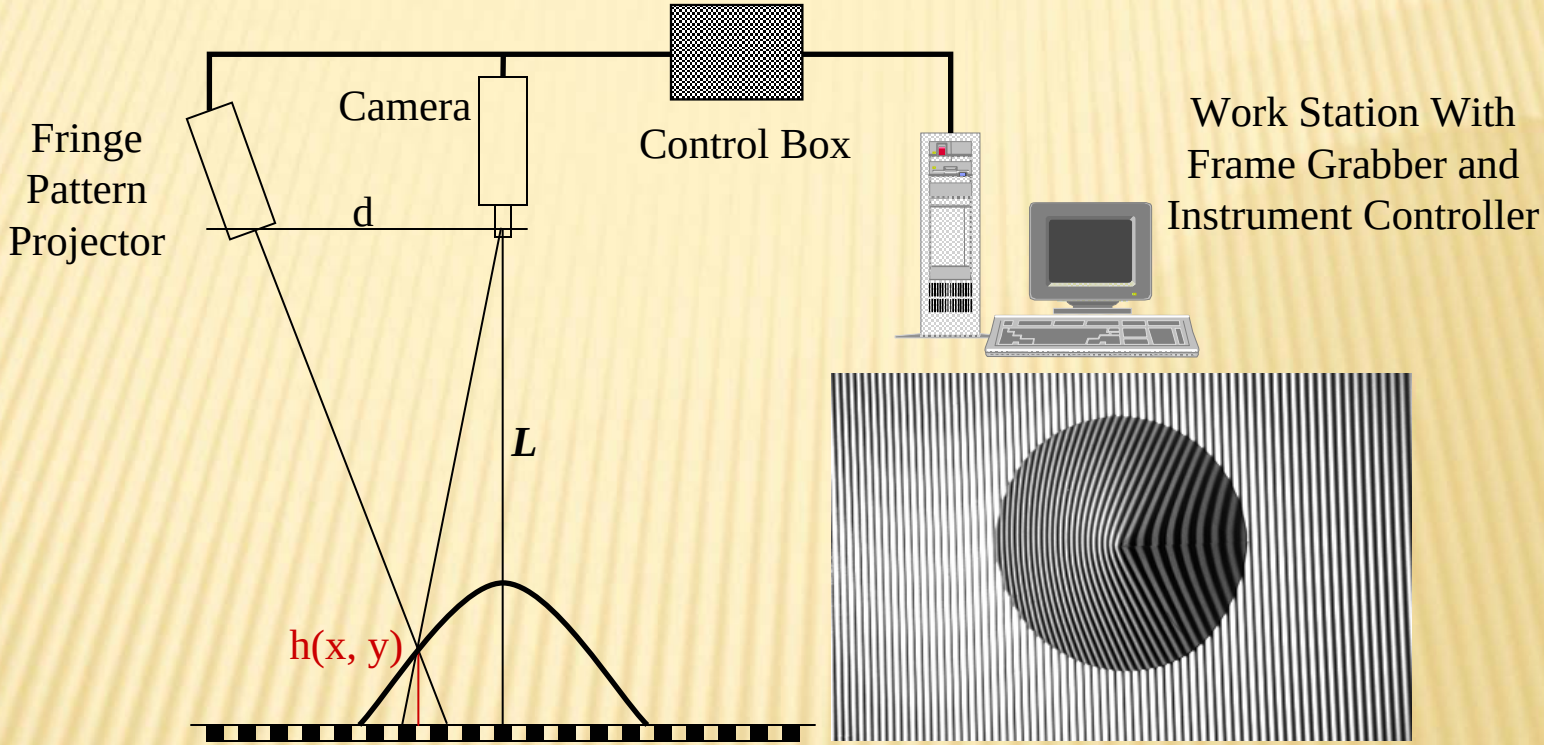
- Need for FTP
- Overview of FTP Technique
- FTP at Maximum Tank Distance
- Identification and Characterization of Uncertainties
  - Inherent
  - Instrumental
- Summary
- Path Forward

# Bottom of Hanford Tank C-106

CH2MHILL
Hanford Group, Inc.

Improved tools for residual waste volume determination are expected to provide site operators and regulators with verifiable information that can be used in determination of closure timelines.

# Principle of the FTP Technology

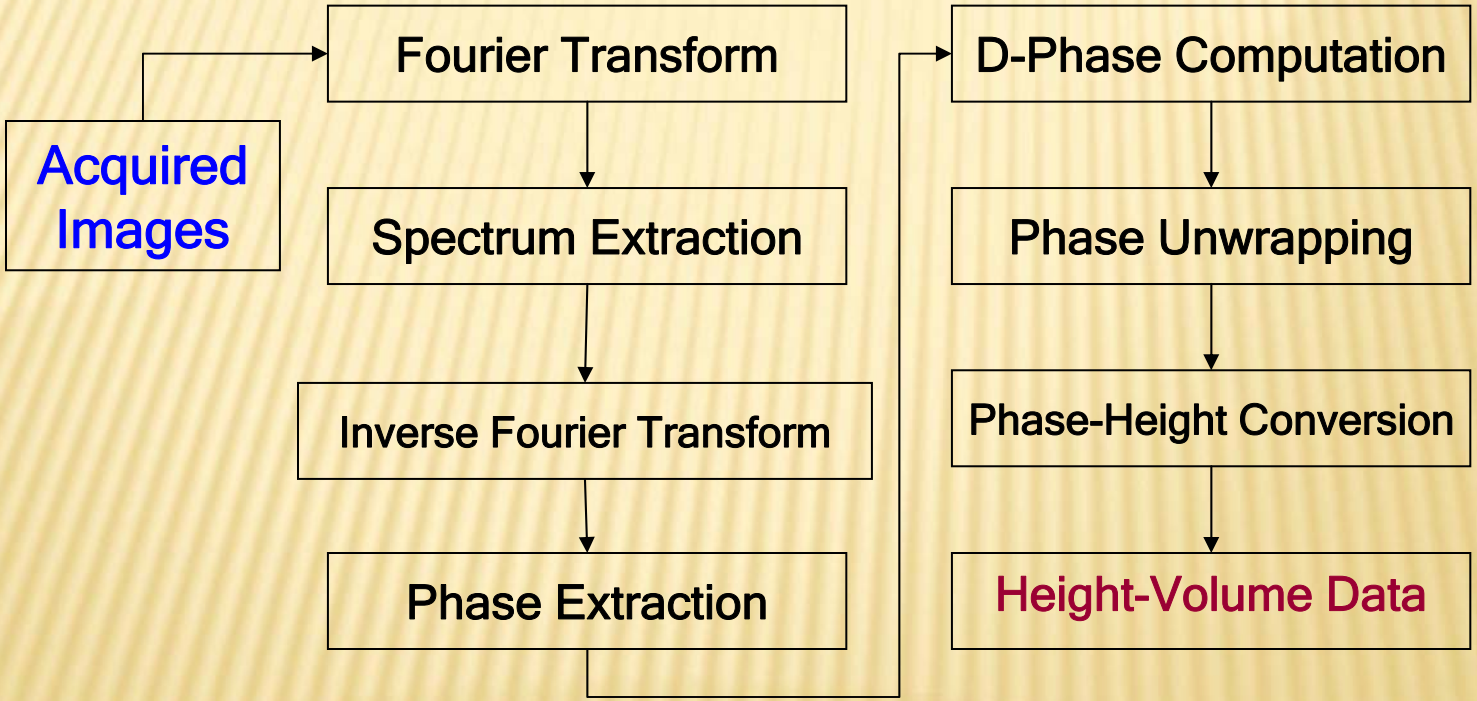



$$h(x, y) = \frac{L\Delta\Phi(x, y)}{\Delta\Phi(x, y) - 2\pi f_0 d}$$

Where:
h = height
$\Delta\Phi$ = phase variation
$f_0$ = fundamental frequency

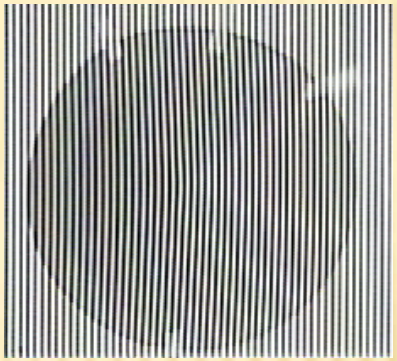
# FTP Process Flow Chart

Fourier Transform Profilometry (FTP) - A 3-D shape measurement technique. Projecting a fringe pattern upon target surface and observing its deformation from a different view angle.

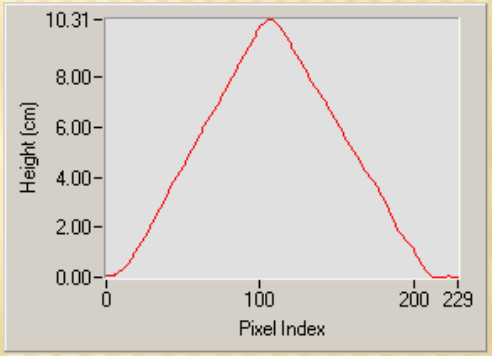


# Typical Measurement Results under Simulated Conditions

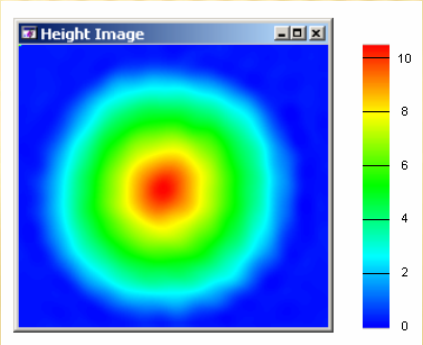
- Distance between camera and target: 15 ft
- Distance between camera and projector: 8”
- Ronchi filter: 250 lines/inch
- Target: paper cone with base diameter Φ = 26.7 cm (~10.5”) and peak height = 10.4 cm (~4”)



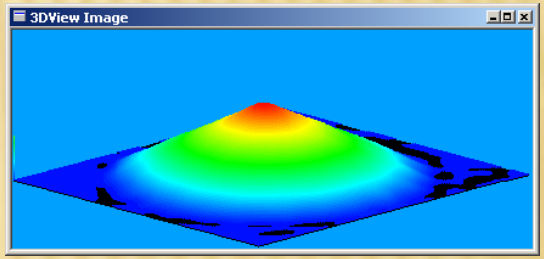
Target




Reconstructed 1D Profile



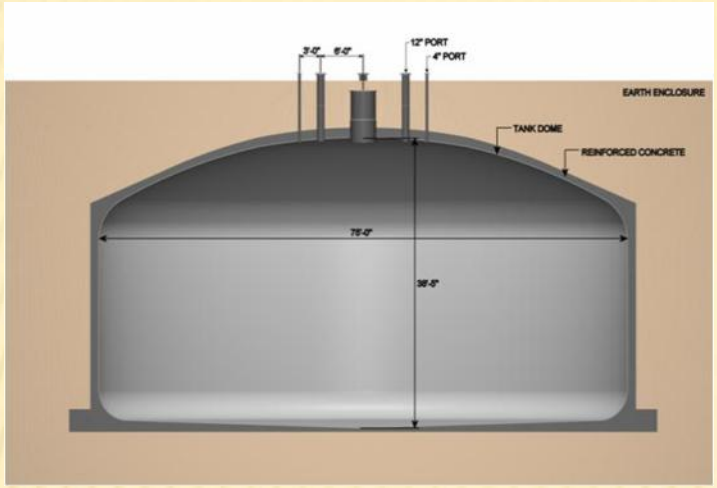

Reconstructed 2D Profile

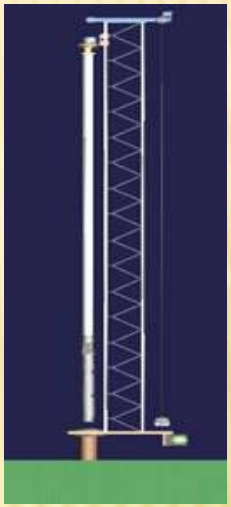



Reconstructed 3D Profile

| | Target | Measured | Error |
|---|---|---|---|
| Peak Height (cm) | 10.4 | 10.31 | 0.9% |
| Volume ($cm^3$) | 1941.00 | 1962.73 | 1.1% |

# Maximum Observation Distance : 53 ft at 62° 25 ft Above



## Design Goals for In-Tank FTP Probe Inspection System

- Must be deployable through 4" ID riser.
- Insertion depths of 9 to 30 ft.
- Ability to pan 360 º and to tilt 120°.
- Illumination must be provided.
- Deployment by 2 technicians wearing protective garment & heavy gloves w/o use of "crane."
- Max. riser loads of 500 lb axial & 250 ft-lb bending moment.
- Operator lifting limitation of 40 lbs will require breakdown into subassemblies.

# FTP Results at Maximum Tank Distance

S3 S4 S6

| Target | True Volume ($cm^3$) | Measured Volume ($cm^3$) | Absolute Error ($cm^3$) | Relative Error (%) |
|---|---|---|---|---|
| S3 | 1954 ± 10 | 2057 | +103 | +5.3 |
| S3 | 1954 ± 10 | 2039 | +85 | +4.4 |
| S3 | 1954 ± 10 | 2085 | +131 | +6.7 |
| S3 | 1954 ± 10 | 2105 | +151 | +7.7 |
| S4 | 1071 ± 6 | 1089 | +18 | +1.7 |
| S4 | 1071 ± 6 | 1129 | +58 | +5.4 |
| S4 | 1071 ± 6 | 1081 | +10 | +0.9 |
| S4 | 1071 ± 6 | 1087 | +16 | +1.5 |
| S6 | 647 ± 4 | 683 | +36 | +5.6 |
| S6 | 647 ± 4 | 686 | +39 | +6.0 |
| S6 | 647 ± 4 | 695 | +48 | +7.4 |
| S6 | 647 ± 4 | 711 | +64 | +9.9 |

Average Relative Error +5.2 %

# Current Focus: Identification and Characterization of Measurement Uncertainties (Inherent and Instrumental)

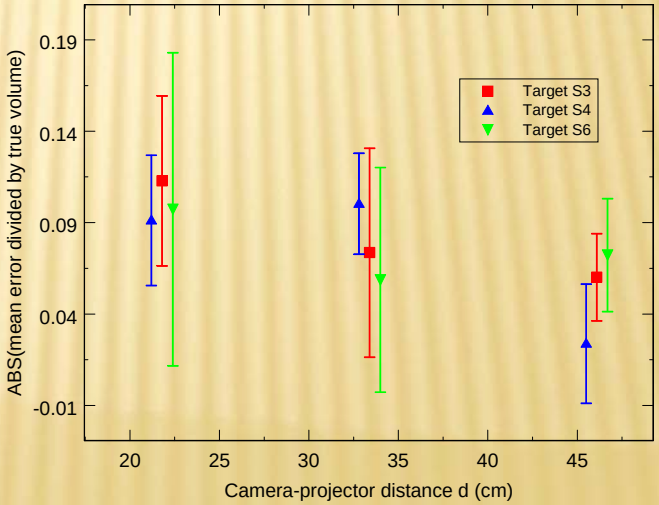
- **Inherent**

$$h(x,y) = \frac{L\ \Delta\Phi(x,y)}{\Delta\Phi(x,y) - 2\pi d f_0}$$

where h = height of object
$f_0$ = fundamental frequency
d = camera-projector separation
$\Delta\Phi$ = phase variation
L = camera-reference plane distance

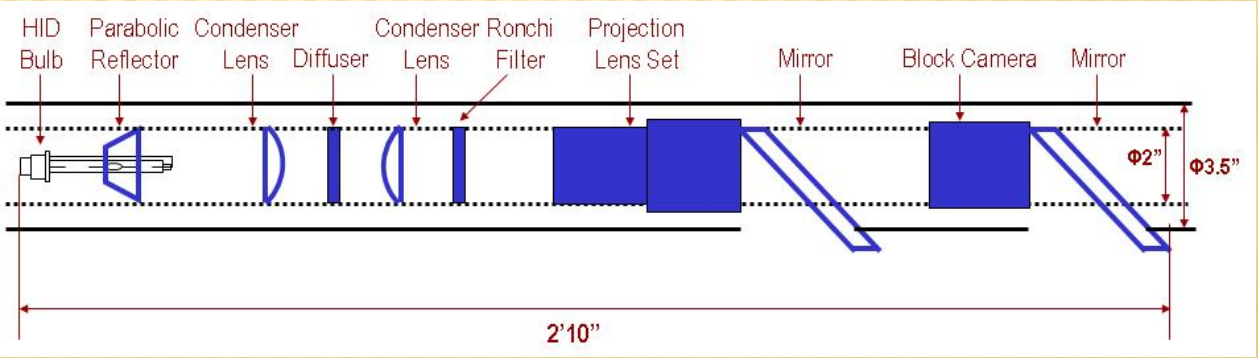
  - Camera-projector separation

$$\frac{\partial h}{\partial d} \approx -\frac{h}{d}$$



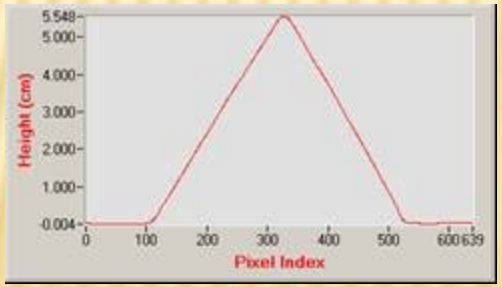
# Current Focus: Identification and Characterization of Measurement Uncertainties (Inherent and Instrumental)

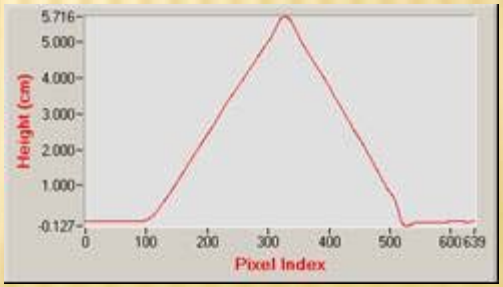
- Instrumental
  - Imager
    - Pixels, zoom level, sampling rate
    - Shutter speed, gain
    - Minimum illumination
    - Signal-to-noise ratio
    - Effect of gamma radiation
  - Projected light field uniformity and intensity
  - Fringe pattern focus
  - Thermal effects, instrument warm-up



# Effect of Camera Resolution and Zoom Level

- For similar field of view (FOV), no obvious difference for increasing imager resolution.
- It was found that the zoom level should be at least 11000 (≈x5). [Zoom levels are 0 to 16384 (0 to x25) for SONY 78B.]
- Better results are observed with focused fringe pattern - others have reported that defocusing may lead to better results.



# Effect of Sampling Frequency

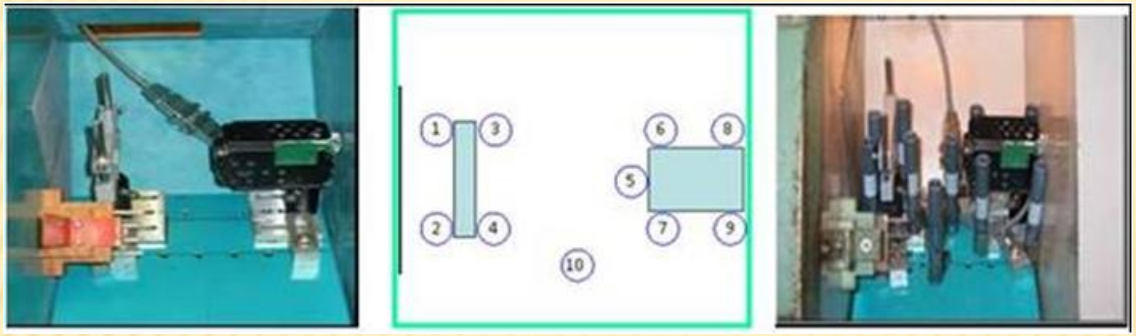
The signal we are sampling includes not just the fundamental of the fringe pattern at spatial frequency $f_0$, but also includes harmonics at $2f_0$, $3f_0$, etc. In order to separate out the $n$th harmonic, it is necessary that the ratio $m$ of the sampling frequency to the fundamental fringe frequency $f_0$ be

$$m \geq \frac{4}{3}(n+1)$$

| Distance L (cm) | $f_0$ (lines/cm) | Pixels/cm | $m$(expt) (pixels/line) |
|---|---|---|---|
| 1615.6 | 0.747 | 33.5 | 44.8 |
| 652.4 | 1.233 | 26.7 | 21.7 |
| 434.8 | 1.863 | 20.2 | 10.8 |
| 232.6 | 3.481 | 21.9 | 6.3 |

For $n = 3$, $m$ must be greater than about 5.33; for $n = 2$, $m$ must be greater than about 4.0. In general, only $n = 2$ harmonic has any significant intensity.

# Effect of Gamma Radiation on Camera Performance

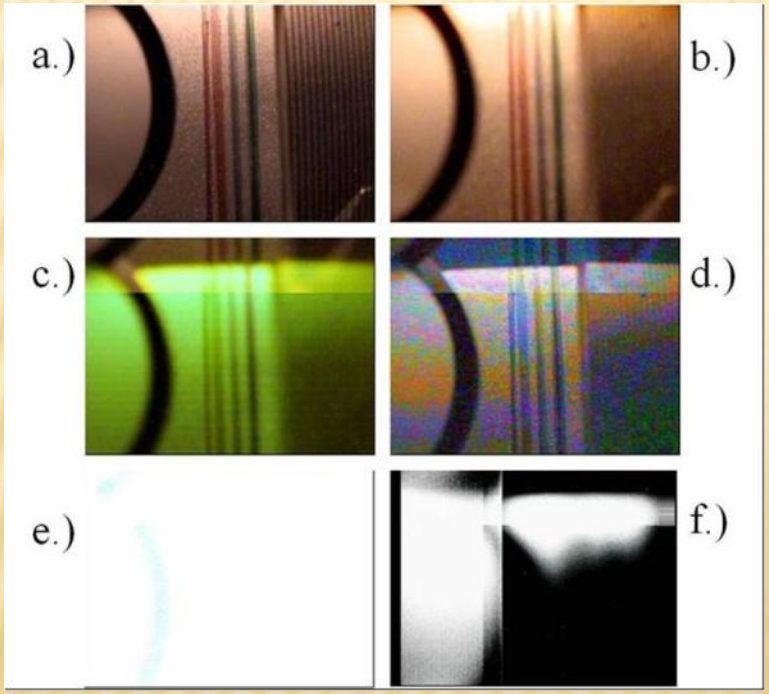



| Location | R/hour |
|---|---|
| 1 | 54 |
| 2 | 60 |
| 3 | 34.5 |
| 4 | 32.7 |
| 5 | 21.6 |
| 6 | 12.6 |
| 7 | 15 |
| 8 | 12 |
| 9 | 12 |
| 10 | 3 |

Beginning

193rd hour

198th hour

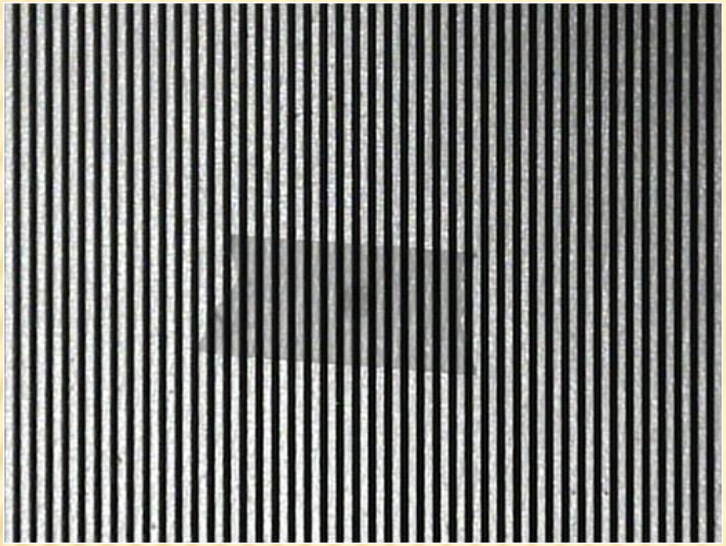



182nd hour

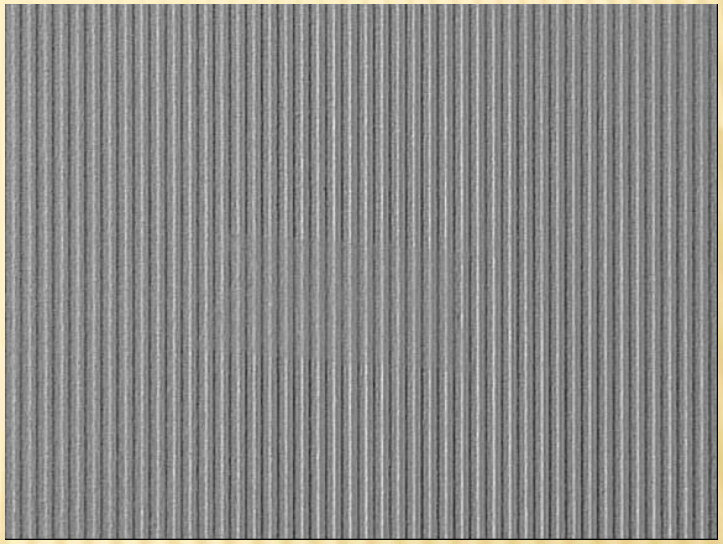
197th hour

207th hour

# Investigation of Camera Stability
# Time-Dependent Fringe Pattern Shift



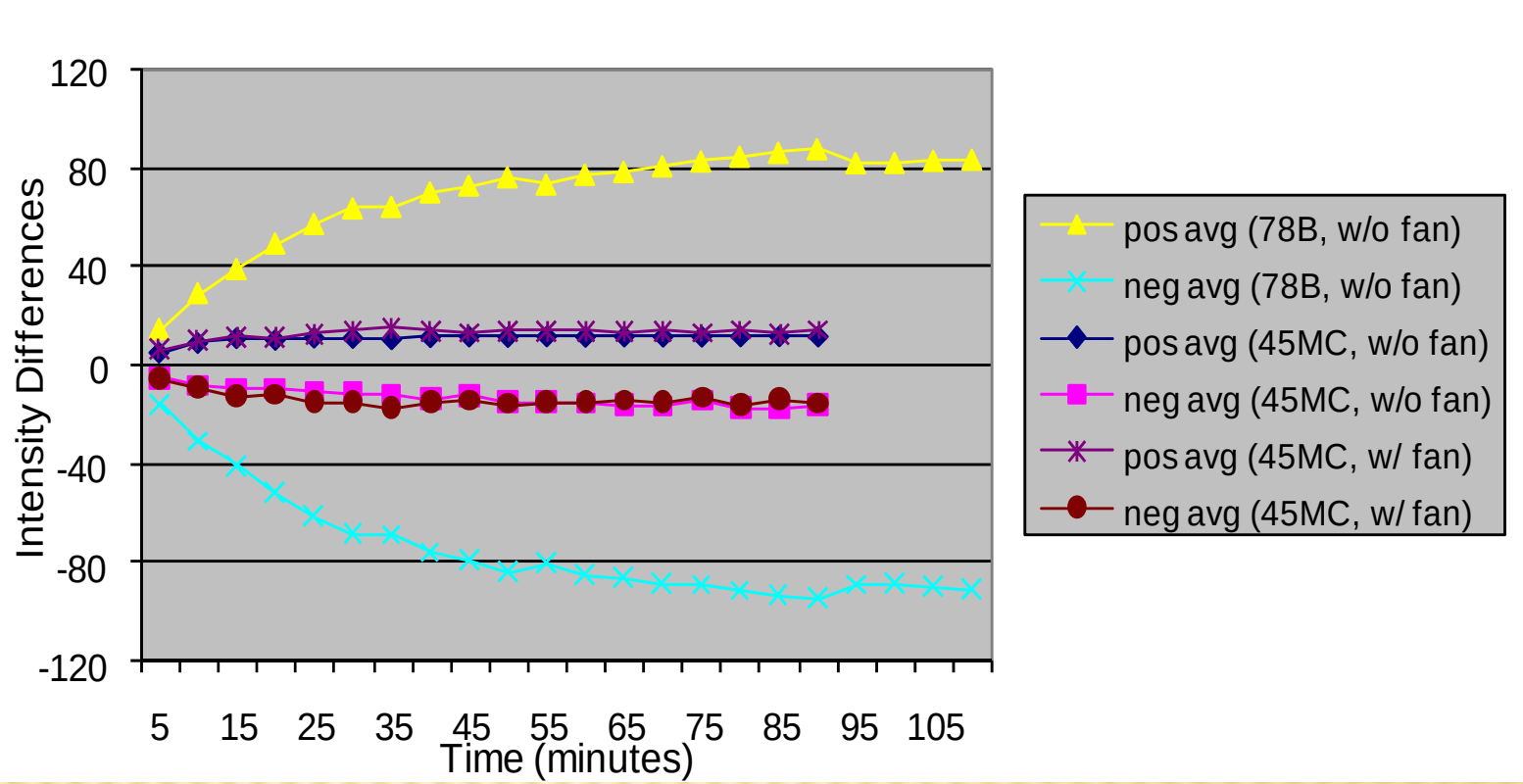
**Fringe pattern (image # 1)**



**Result obtained by subtracting image # 1 from image # 10. If no change, this would be all black.**

**Images automatically recorded at 5 minute intervals.**

# Investigation of Fringe Pattern Shifts Different Imagers and Conditions




Intensity differences (positive/negative) relative to first image recorded using SONY FCB-EX78B (color) and SONY FCB-45MC (B&W) cameras with and without cooling fan.

# Camera Stability at Thermal Equilibrium

| Camera | Intensity Difference | Fan | Average | Standard Deviation |
|---|---|---|---|---|
| 78B | Positive | None | 80.83 | 4.53 |
| 78B | Negative | None | -87.60 | 4.48 |
| 45MC | Positive | Off | 11.91 | 0.10 |
| 45MC | Negative | Off | -14.85 | 1.57 |
| 45MC | Positive | On | 13.90 | 0.56 |
| 45MC | Negative | On | -14.68 | 0.91 |

Fluctuations in intensity differences (relative to first image recorded) at thermal equilibrium (times ≥ 45 minutes after cameras turned on).

B&W imager (45MC) has better stability than color imager (78B) as indicated by standard deviations.

# Comparison of 78B and 45MC Cameras

| | SONY FCB-EX78B | SONY FCB-45MC |
|---|---|---|
| Format | color | black & white |
| Pixels | 680K | 380K |
| Optical Zoom | 25x | 18x |
| Digital Zoom | 12x (300x with optical zoom) | 12x (216x with optical zoom) |
| Lens Focal Length | 2.4 mm (Wide)<br>to 60 mm (Tele) | 4.1 mm (Wide)<br>to 73.8 mm (Tele) |
| Min. Illumination | 2.5 lux (1/60$^{th}$ sec, NTSC) | 0.01 lux (1/60$^{th}$ sec, EIA) |
| S/N Ratio | 49 dB | 50 dB or more |
| Electronic Shutter Speed | ¼ to 1/10,000 sec | 1/60 to 1/10,000 sec |
| Gain | -3 to 28 dB, 16 steps | -3 to 28 dB, 2 dB steps |
| Dimensions | 50.0 x 57.5 x 81.8 mm | 50.0 x 57.5 x 88.5 mm |
| Other Factors | Equivalent to currently used Hanford imaging cameras | |

Camera characteristics indicate that the B&W imager requires a significantly lower minimum illumination than color imager. Taken all together, a B&W camera with sufficient pixels will be considered for adoption.

# Summary of Recent Results

- Efforts to minimize instrument errors
  - Maximize camera-projector separation to extent possible
  - Minimum zoom level has been determined
  - Sampling frequency sufficient to avoid including harmonics during FFT process
  - Imager dies from gamma radiation before significant degradation of Ronchi filter and diffuser
  - Warm-up time much longer for color camera (78B) than for B&W camera (45MC)
  - B&W camera (45MC) has better stability at thermal equilibrium than color camera (78B)

# Path Forward

- Original process sequence developed with previous tank farm contractor.
  - Initiated FTP technical feasibility study to document measurement uncertainties
  - Future tasks include stitching, curved surfaces, etc.
- Need new contact at Hanford and need to further discuss technology with SRS
- What errors will be acceptable for verifying residual volumes? 5,10, 20% ?
- Re-evaluation of optical configuration for 2nd generation prototype
- Field testing – TVA tanks MS
- Technology Transfer

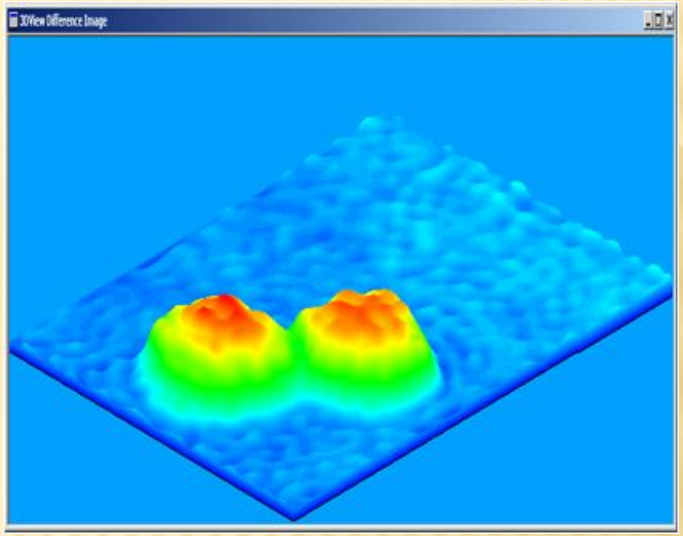
# Acknowledgments

We wish to thank Dennis Hamilton (CH2MHILL Hanford), Rick Raymond (CH2MHILL Hanford), and Gary Josephson (PNNL) for their guidance and assistance for this effort.

We also wish to thank Sharon Marra and Jeff Griffin of SRNL for their encouragement.

This effort was funded by the U.S. Department of Energy's Office of Environmental Management through Cooperative Agreement DE-FC01-06EW-07040.

# Questions ?

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