Fourier Transform Profilometry (FTP) for Residual Waste Volume Determinations

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Savannah River/Hanford/Idaho Technical Exchange
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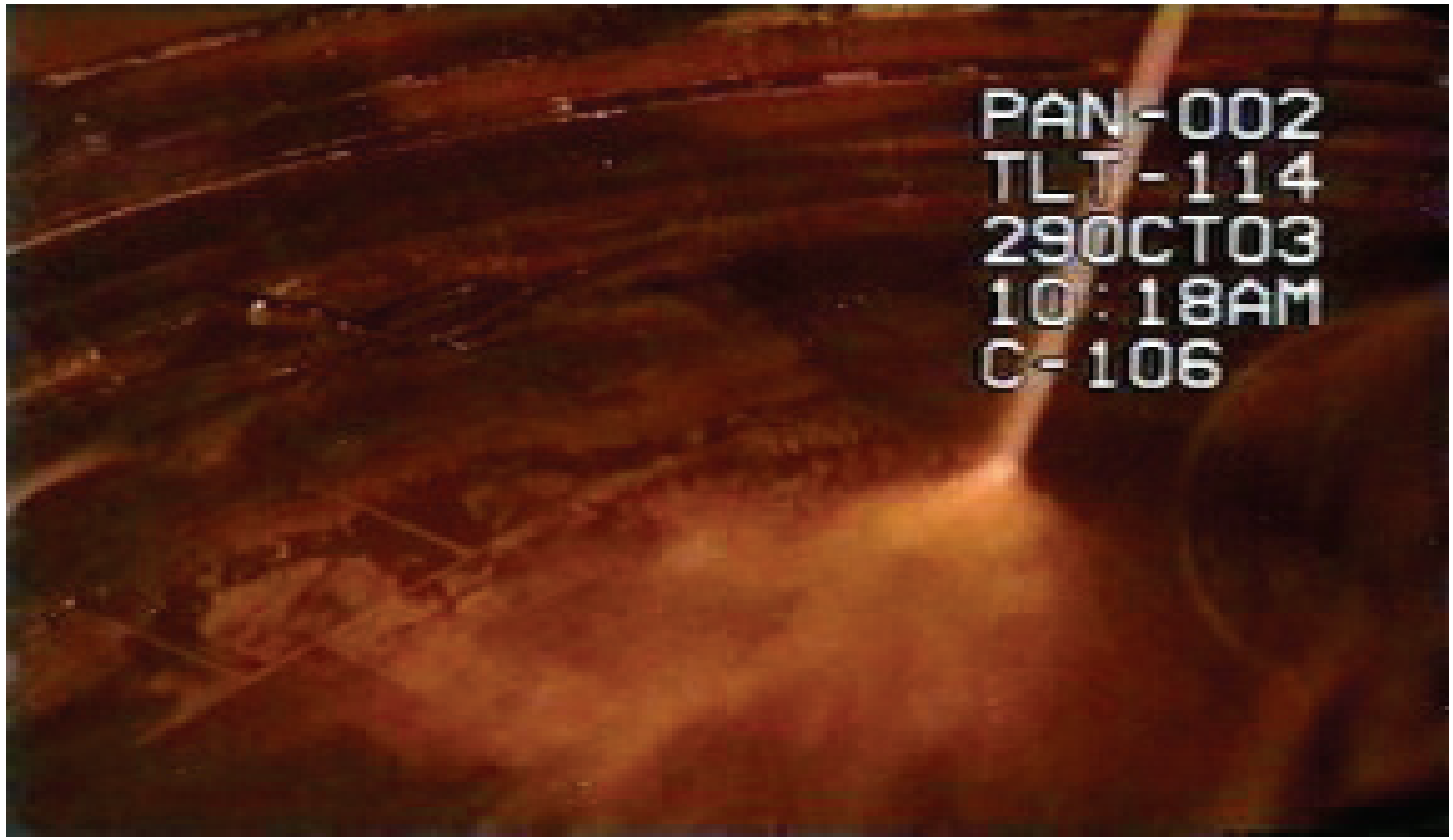
Bottom of Hanford Tank C-106 With ~2.5 cm (1”) Granular Solids



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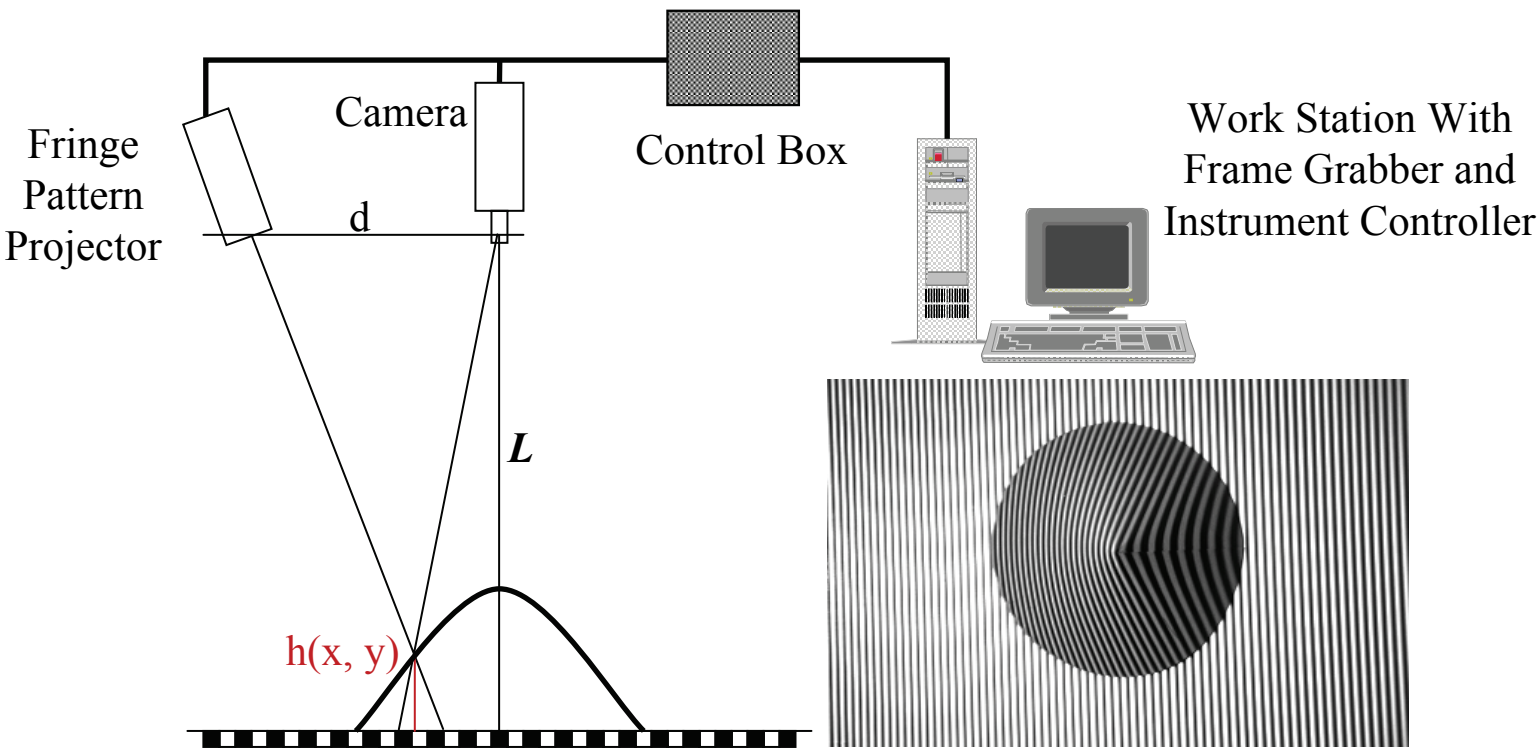
Principle of the FTP Technology

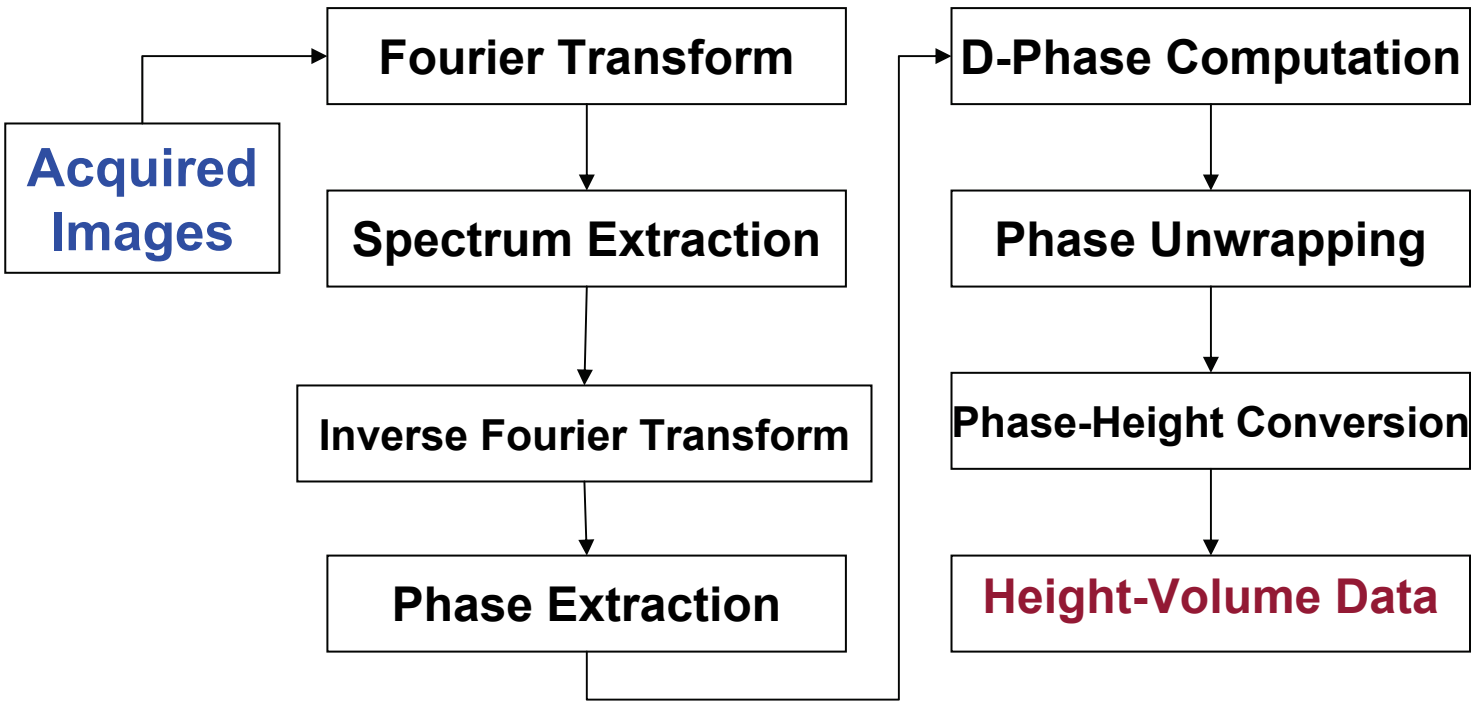


$$h(x, y) = \frac{L\Delta\Phi(x, y)}{\Delta\Phi(x, y) - 2\pi f_0 d}$$

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

FTP Process Flow Chart

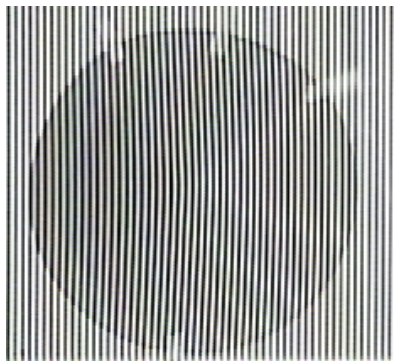
Fourier Transform Profilometry (FTP) - A 3-D shape measurement technique. Projecting a fringe pattern upon target surface and observing its deformation from a different view angle.



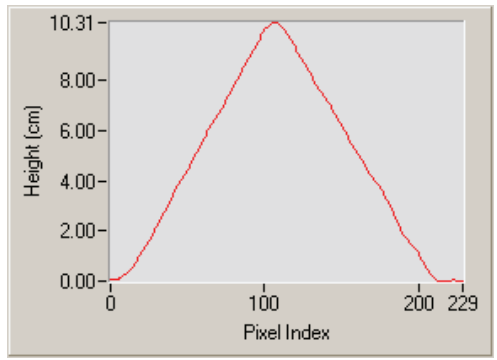
Typical Measurement Results under Simulated Conditions

- 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”)

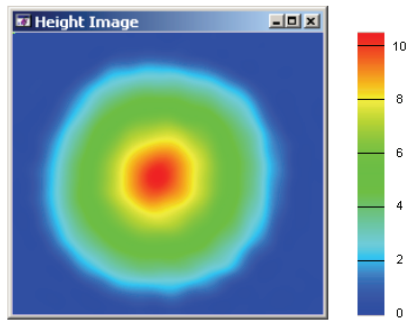
	Target	Measured	Error
Peak Height (cm)	10.4	10.31	0.9%
Volume (cm^3)	1941.00	1962.73	1.1%



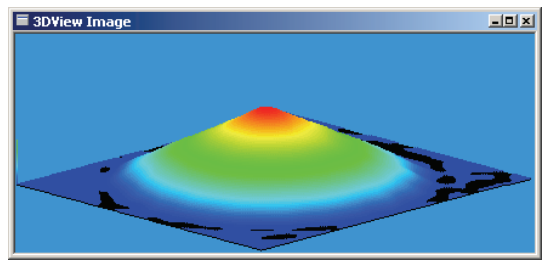
Target



Reconstructed 1D Profile



Reconstructed 2D Profile



Reconstructed 3D Profile

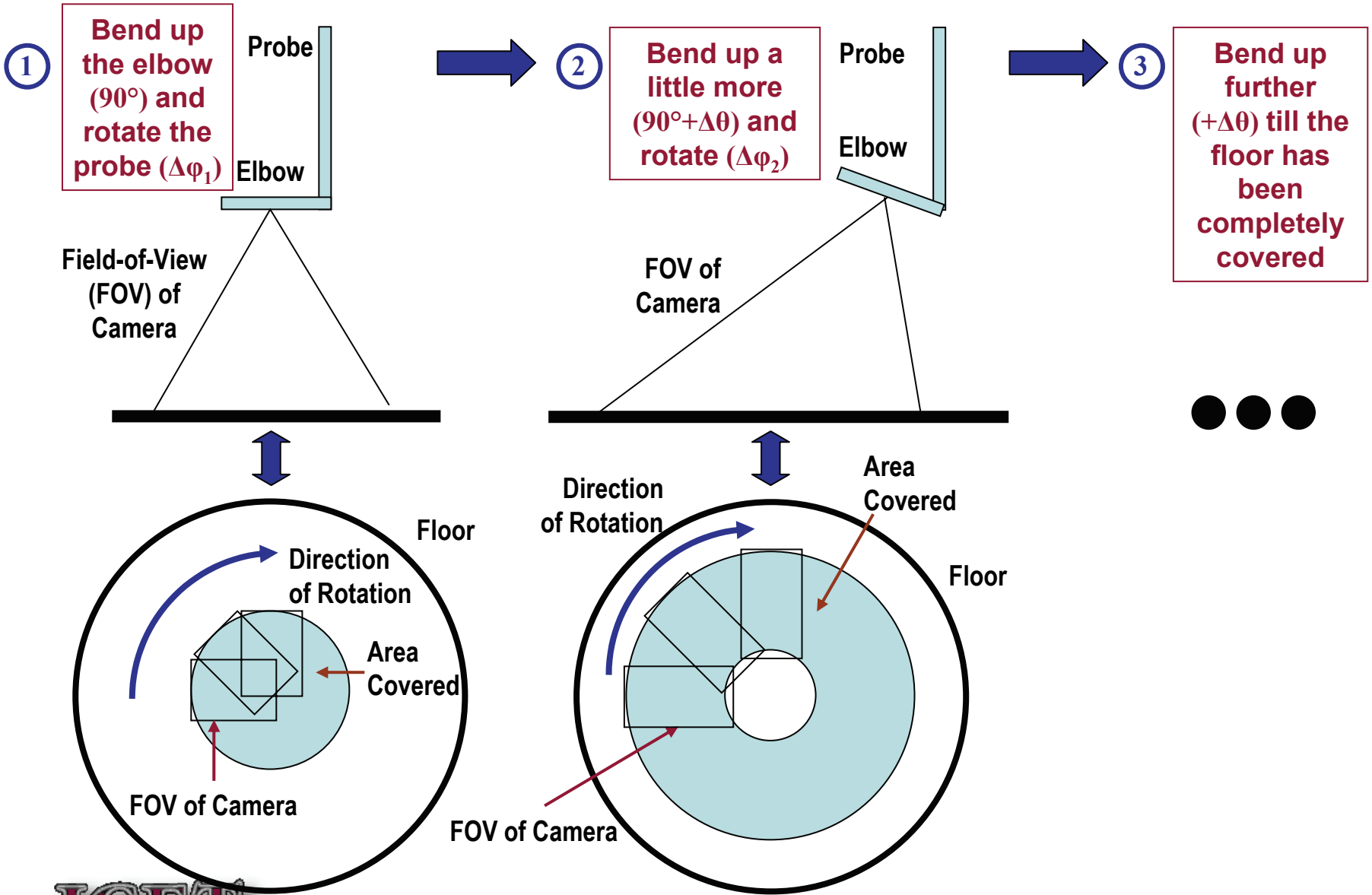
FTP Probe System

for Hanford Waste Tanks

Design Goals for In-Tank Probe Inspection Systems

- 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.

Plan for Floor Measurement within Tanks



Multi-Stage Measurement Simulation

- **Stage 1: Flat "tank floor." Analyze objects within single image.**
- **Stage 2: Flat "tank floor." Stitch together results.**
- **Stage 3: Bowl-shaped "tank floor." Analyze objects within single image.**
- **Stage 4: Bowl-shaped "tank floor." Stitch together results.**

Multi-Stage Measurement Simulation

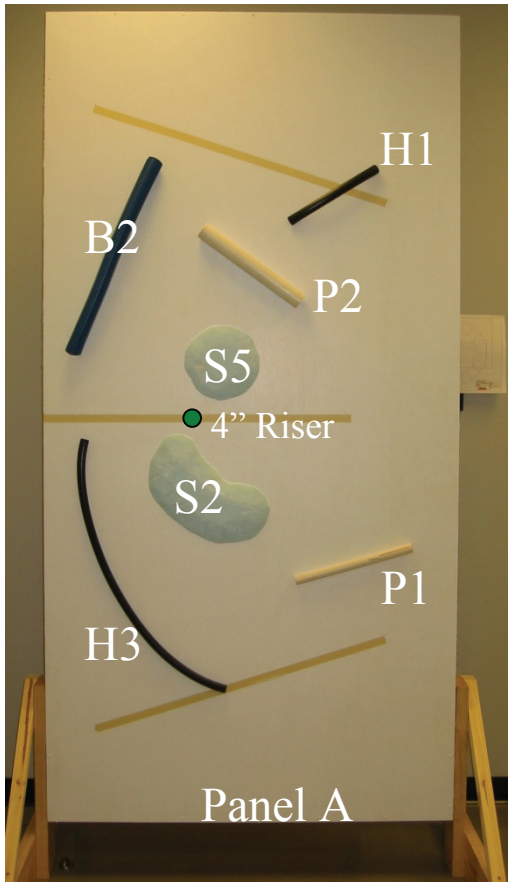
- **Stage 5: Full-scale simulated deployment of FTP probe system at ICET.**

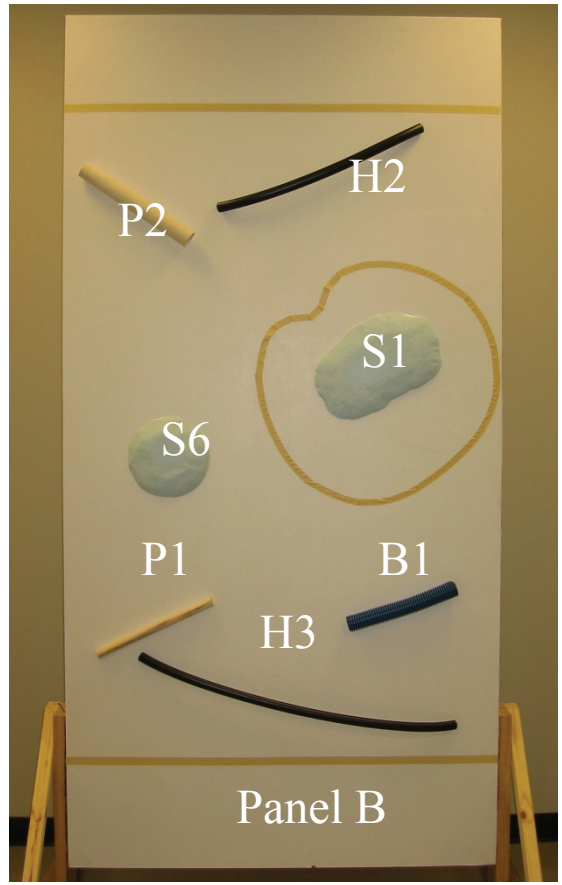
- **Stage 6: Demonstration of FTP probe system at Hanford's Cold Test Facility (CTF).**

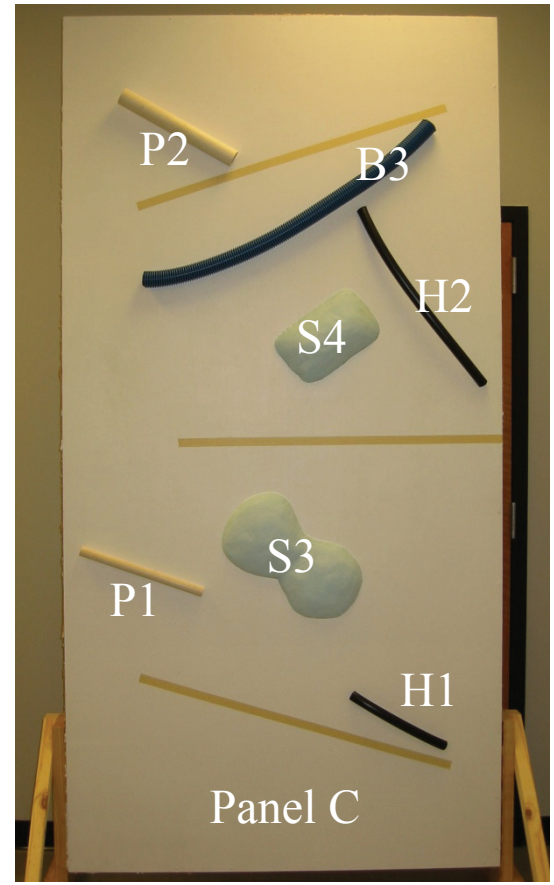
FTP Performance Evaluation

Stage 1 Results

Objects Layout on 20-ft Flat Tank Floor

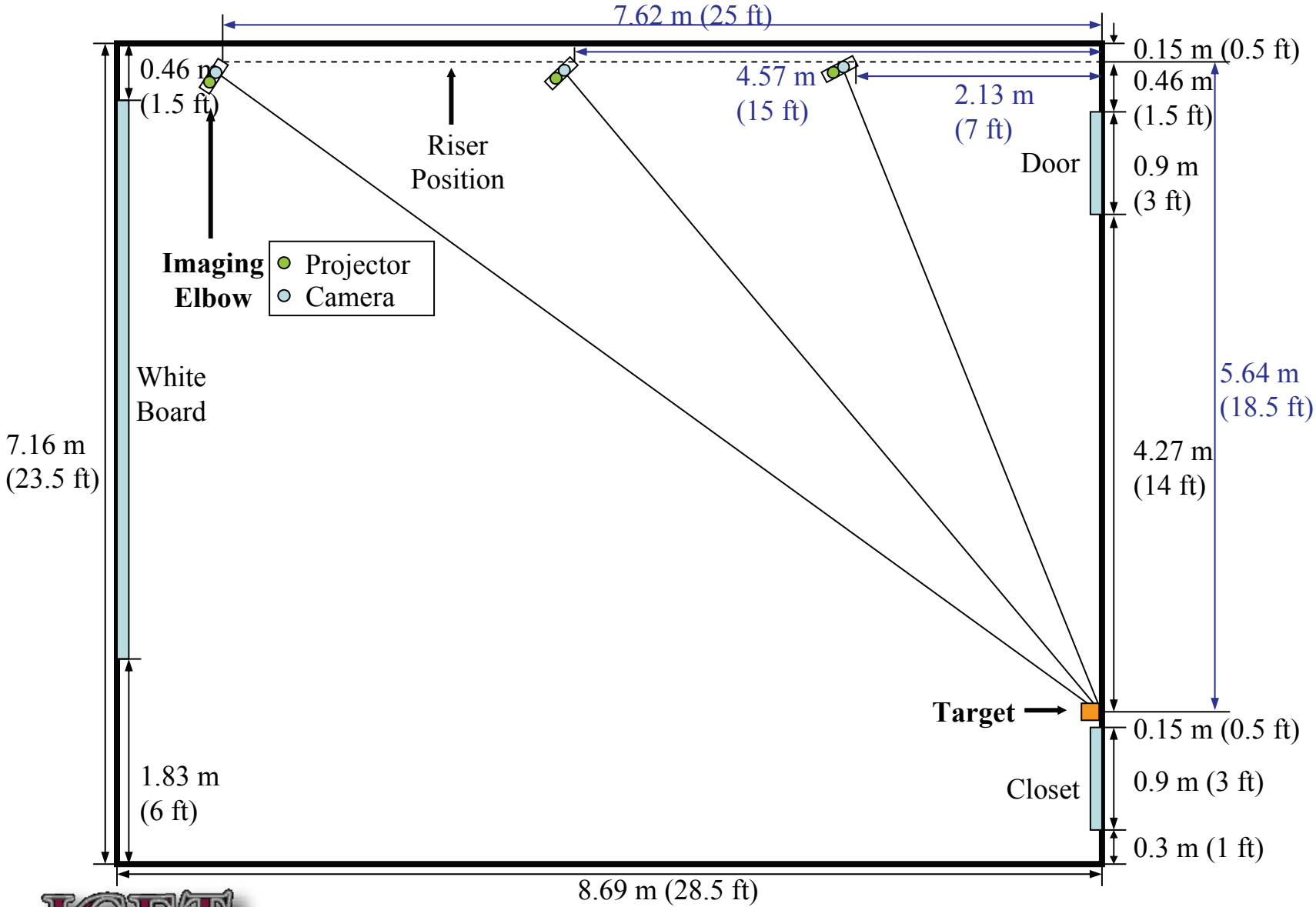






B#: 1 7/8" OD blue hoses (in # of feet long)
P#: 14" long PVC pipes (in # of inches O.D.)
H#: Black hose (ellipse with major 1 1/8" & minor 61/64" OD) (in # of feet long)
S#: Unknown target # made of styrofoam

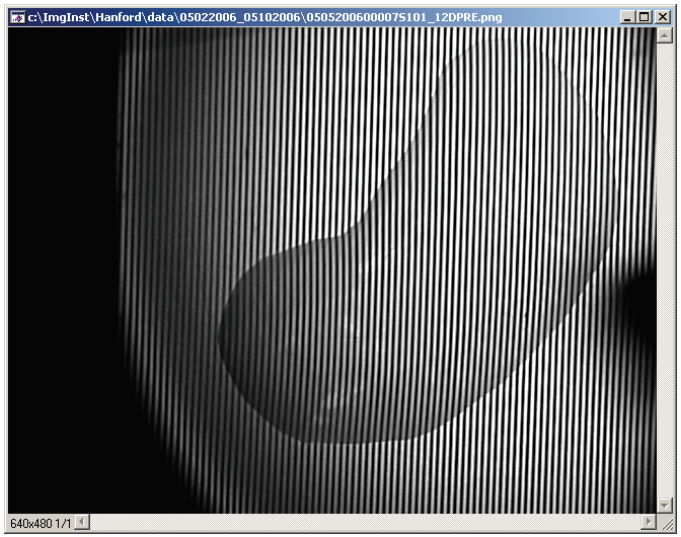
Layout for Viewing Targets on Panel C



Determination of Non-Descript Volumes by Traditional Means

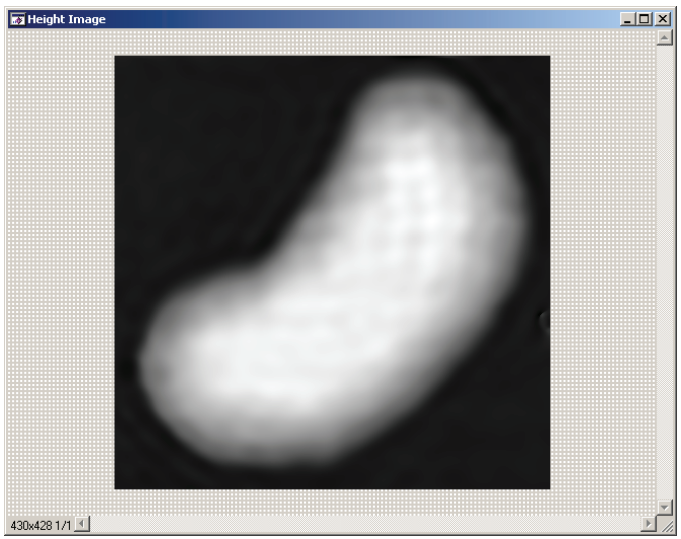
Target	# Replicates	Average Volume (cm^3)	Std Dev (cm^3)	Relative Uncertainty
S1	10	1027.8	12.2	1.19%
S2	4	1070.2	7.2	0.67%
S3	4	1954.1	10.2	0.52%
S4	4	1070.7	5.6	0.52%
S5	4	421.8	4.6	1.09%
S6	4	647.1	3.8	0.58%

Typical FTP Reconstructed Profiles for S2

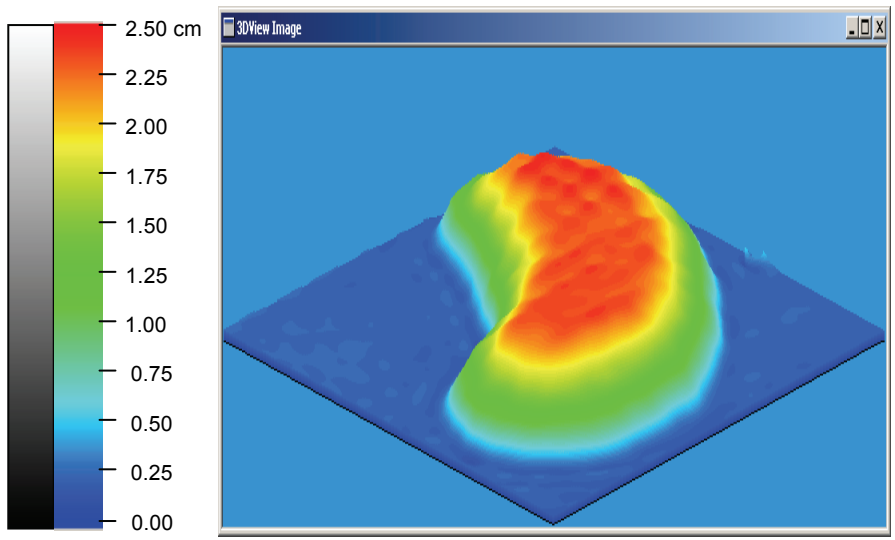


Original Image

Conditions: 7 ft away, right under
Measured volume: 1120 cm^3
True volume: 1070 ± 7 cm^3
Error: 50 cm^3 (4.7%)

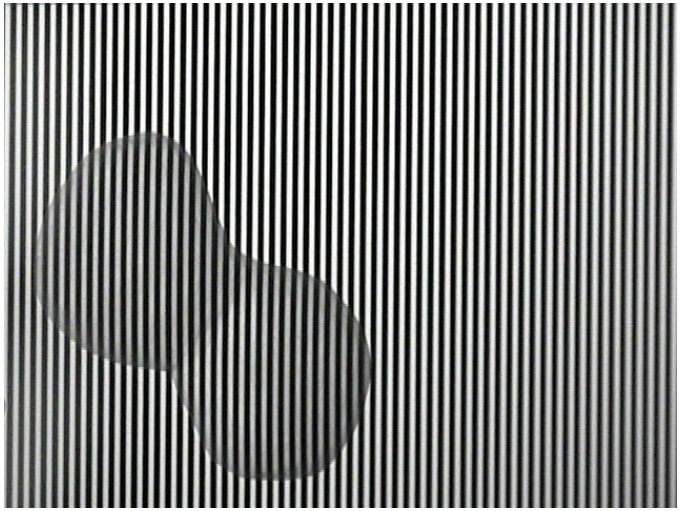


2-D Reconstruction



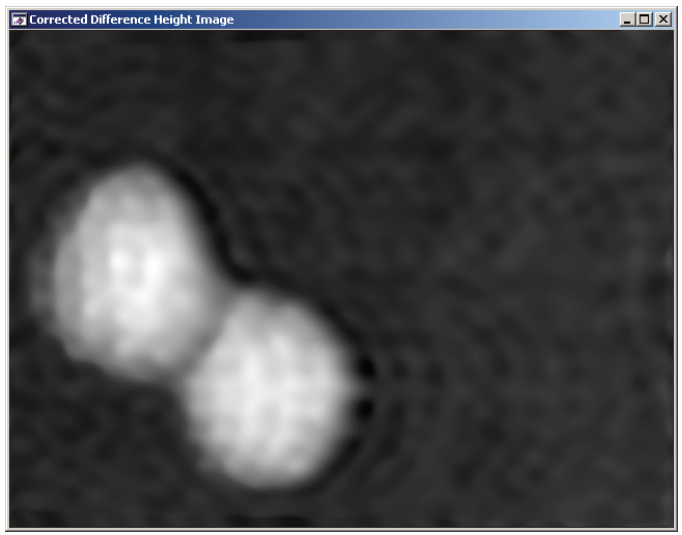
3-D Reconstruction

Typical FTP Reconstructed Profiles for S3

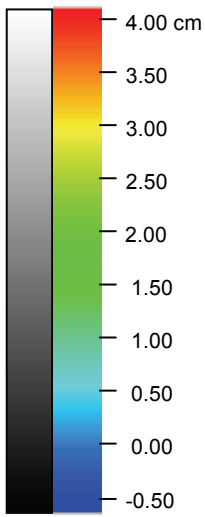


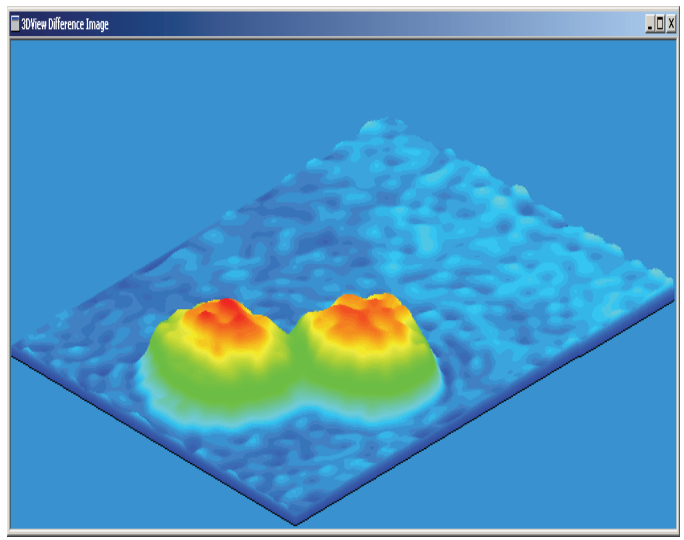
Original Image

Conditions: 25 ft away, 18.5 ft offset, 31.1 ft diagonal
Measured volume: 1804 cm^3
True volume: 1954 ± 10 cm^3
Error: -150 cm^3 (-7.7%)



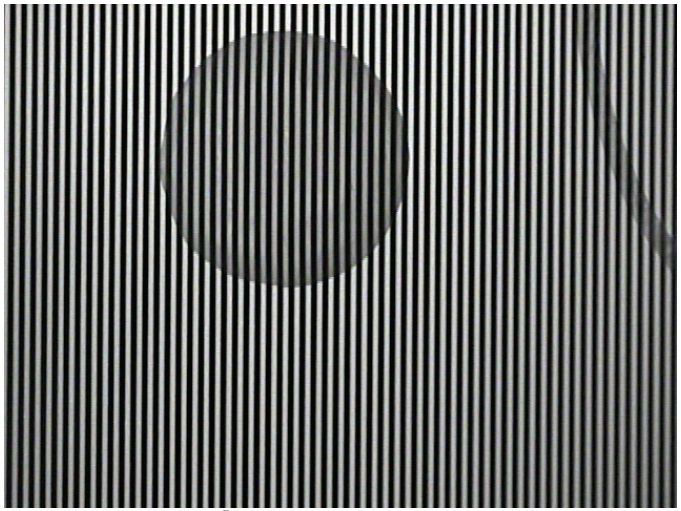
2-D Reconstruction





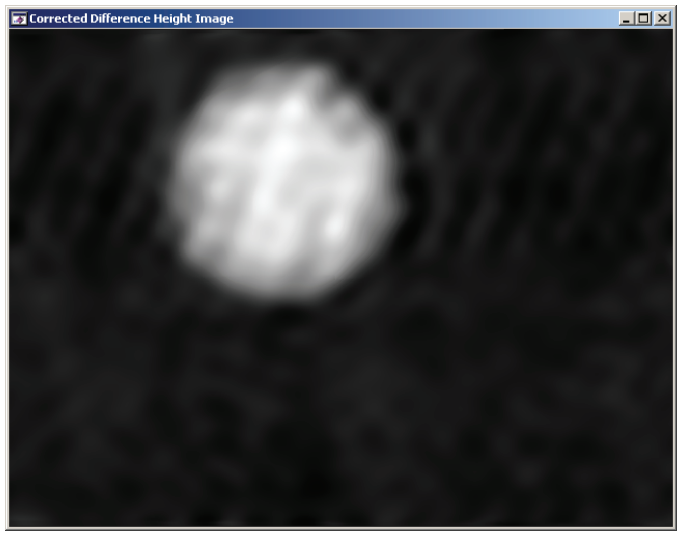
3-D Reconstruction

Typical FTP Reconstructed Profiles for S6

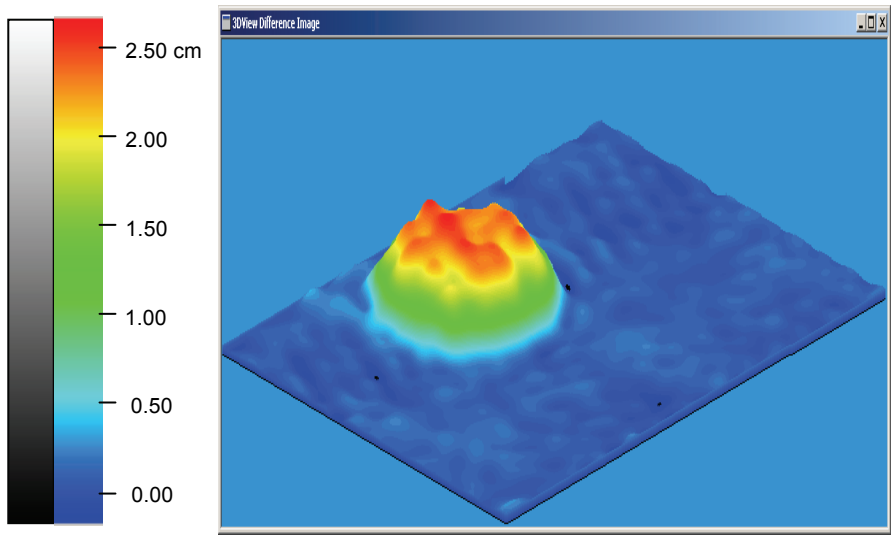


Original Image

Conditions: 25 ft away, 9 ft offset,
26.6 ft diagonal
Measured volume: 665 cm^3
True volume: 647 cm^3 ± 4 cm^3 (1 σ)
Error: 18 cm^3 (2.8%)



2-D Reconstruction



3-D Reconstruction

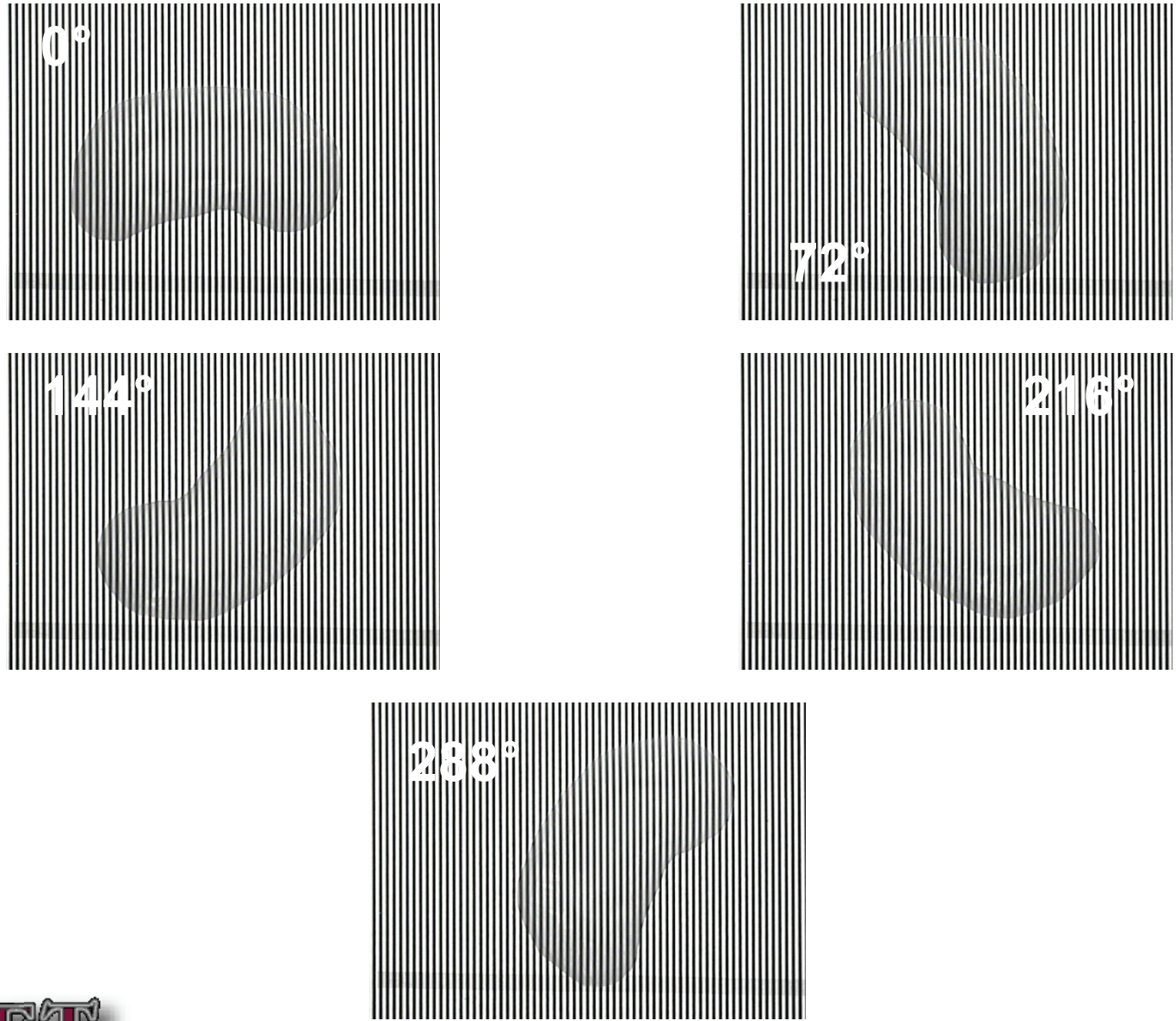
FTP Measurements of Non-Descript Targets

Panel	Target	Distance (ft)	Offset (ft)	FTP Volume (cm^3)	True Volume (cm^3)	Absolute Error (cm^3)	Relative Error (%)
B	S1	25	9	1093	1028 ± 12	65	6.3
B	S1	15	9	1033	1028 ± 12	5	0.5
A	S2	25	0	1069	1070 ± 7	-1	-0.1
A	S2	15	0	1133	1070 ± 7	63	5.9
A	S2	7	0	1120	1070 ± 7	50	4.7
C	S3	25	18.5	1804	1954 ± 10	-150	-7.7
C	S3	15	18.5	1719	1954 ± 10	-235	-12.0
C	S4	15	18.5	1117	1071 ± 6	46	4.3
C	S4	15	18.5	967	1071 ± 6	-104	-9.7
A	S5	25	0	358	422 ± 5	-64	-15.2
A	S5	15	0	447	422 ± 5	25	5.9
A	S5	7	0	425	422 ± 5	3	0.7
B	S6	25	9	665	647 ± 4	18	2.8
B	S6	15	9	625	647 ± 4	-22	3.4

Pixel Counting Measurements of "Known" Targets

Panel	Target	Distance (ft)	Offset (ft)	Volume (cm^3)	True Volume (cm^3)	Abs Error	Relative Error
A	B2	25	0	976	1086	-110	-10.1%
A	P1	25	0	201	180	+21	+11.7%
A	P2	25	0	821	721	+100	+13.9%
A	H1	25	0	179	166	+13	+7.8%
A	H3	25	0	574	497	+77	+15.5%
B	B1	25	9	518	543	-25	-4.6%
B	P1	25	9	204	180	+24	+11.8%
B	P2	25	9	695	721	-26	-3.6%
B	H2	25	9	374	331	+43	+13.0%
B	H3	25	9	546	497	+49	+9.9%
C	B3	25	18.5	1376	1629	-253	-15.5%
C	P1	25	18.5	208	180	+28	+15.6%
C	P2	25	18.5	764	721	+18	+10.8%
C	H1	25	18.5	184	166	+18	+10.8%
C	H2	25	18.5	353	331	+22	+6.6%

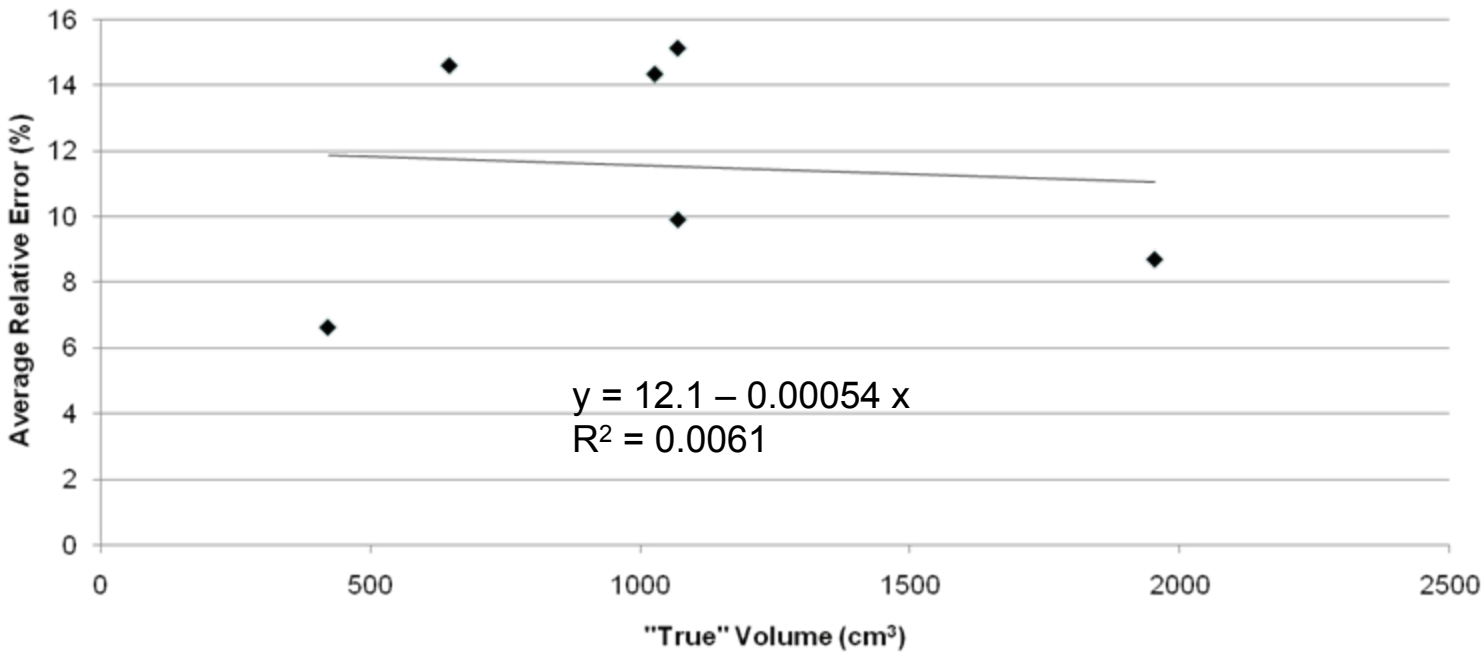
FTP Analyst Dependence



FTP Analyst Dependence

Target	"True" Vol (ft^3)	Rel Error (MM)	Rel Error (PRJ)	Rel Error (OPN)	Rel Error (ZL)
S5	0.01490	103.8%	25.15%	–3.9%	–1.5%
S6	0.02285	48.3%	31.4%	8.05%	4.3%
S1	0.036295	15.1%	25.9%	13.0%	3.4%
S2	0.03779	11.9%	35.8%	9.6%	3.2%
S4	0.03781	50.0%	25.5%	3.5%	0.7%
S3	0.06900	5.8%	19.25%	6.7%	3.0%
Average (Min, Max)		39.15% (1.05, 113.6)	27.2% (7.6, 48.8)	6.2% (–12.2, 28.0)	2.2% (–5.2, 7.8)

FTP Analyst Dependence



Preliminary results indicate that FTP has relatively low analyst dependence and that relative error (%) seems to be independent of target size at least for the targets studied to date.

Summary of Stage 1 Results

On average, FTP technique was able to determine volume of the non-descript targets to within 5.7% of their true value. **Geometric correction was applied to correct for non-perpendicular viewing configuration and hence skewing of images.**

On average, pixel counting technique was able to determine volume of "known" targets to within 10.4% of their true value. **Geometric correction does not seem to affect accuracy of pixel counting results.**

FTP technique has a relatively low analyst dependence.

Recent Improvements

FTP has traditionally be utilized with objects of interest perpendicular to camera. We have implemented an improved algorithm for non-perpendicular images that corrects for fact that viewed areas are keystone-shaped rather than rectangular.

We have developed and extensively tested a stitching procedure that allows us to stitch together volumes for objects that extend beyond single image.

Acknowledgments

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

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