A new chapter for USMs, measure 100% of the Flow Field – results in true Native Accuracy and Flow Field Verification

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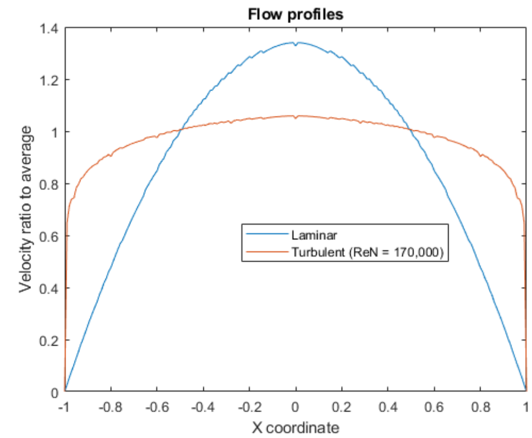
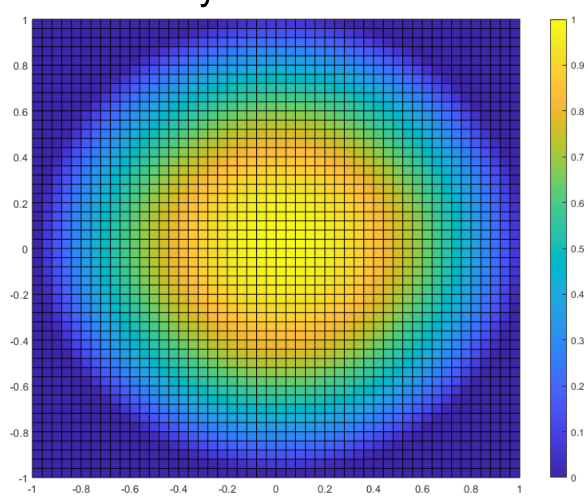
insight
metering systems

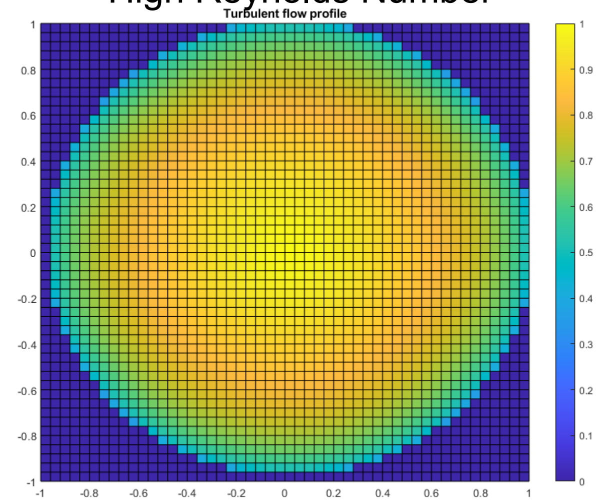
- Flow in a pipe is not uniform
- Even under ideal conditions it varies depending on the Reynolds number (function of dimensions, velocity and viscosity)
- Conditions are rarely ideal
- Upstream conditions – changes everything!
- USMs measure velocity along a chord of the pipe.



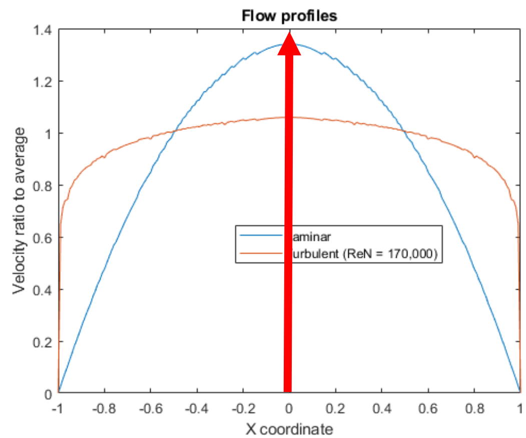
Low Reynolds Number



High Reynolds Number



- USMs – as first introduced – One measurement down the centerline/diameter (or two orthogonal lines). Amazing possibilities! (No moving parts, clamp on, high flow rates)

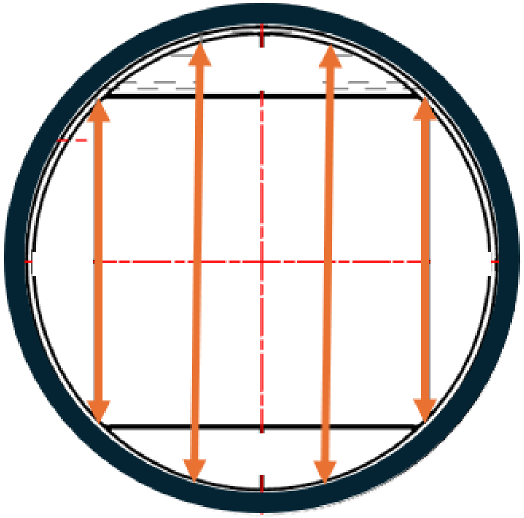


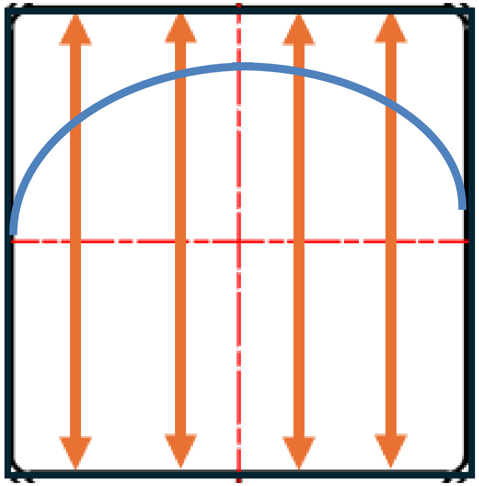
Blue/orange represents that nice smooth velocity profile – red the measure "chord"

- But other than a diagonal path …. everywhere else… **not measured** – this is a real metrological limitation.
- Some manufacturers put "smarts" into their meter – to help improve the meter. [Noting that the measurement over weights the center of the pipe].
- USM a single measurement to **estimate** the whole mean velocity – added various "smarts" put into meter to pick it up by its "bootstraps"
- These meters had a "checkered" history due to installation errors and Reynolds Numbers sensitivity (there is a big difference between the lab and the field).
- Experience says +/- 5% (or worse).

Multi-chord USMs – one more step

- Westinghouse (70’s) realized if they could measure velocities along a few chords/lines across the flow cross section.

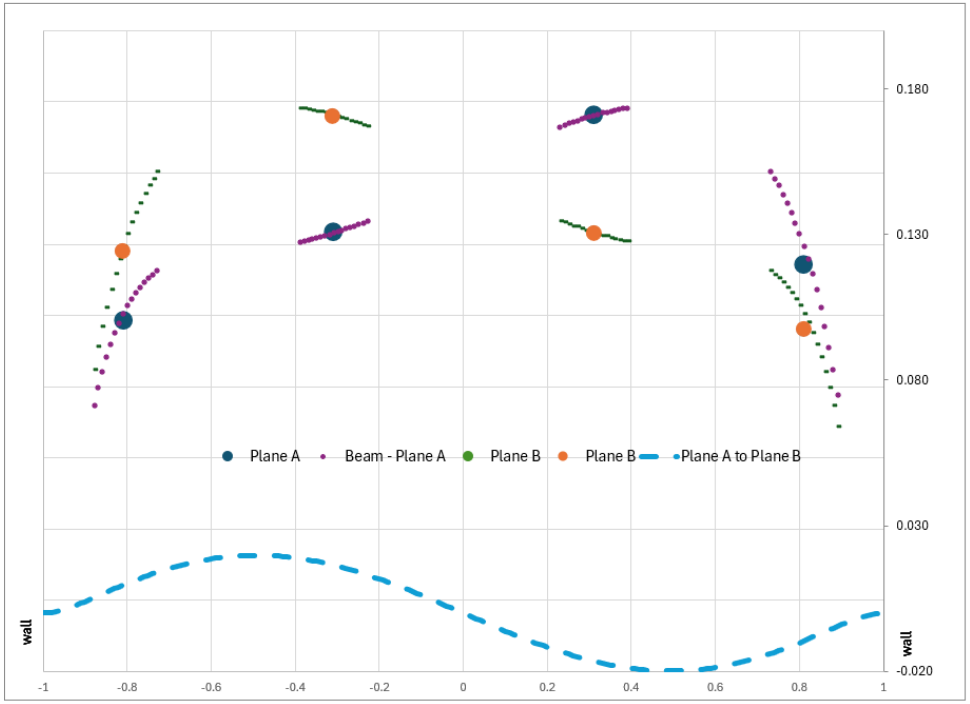




- Now with 4 “chordal” velocities – a lot more information.
- Requires an assumed smoothness and predictable velocities everywhere else – “integrate” by weighting these 4 chords to estimate the mean velocity.
- Everywhere else… is still not measured.
- For cross velocities… initially assumed that path symmetry would address errors.
- Experience: +/- 0.7% to 1.5% for disturbance more than a few diameters away.

Multi-chord USMs – another step forward

- ASME PTC 18.1 – Codified using 8 paths in 80's – ASME recognized that assuming symmetry in cross velocities… was weak – at best in cancelling errors and added cross paths



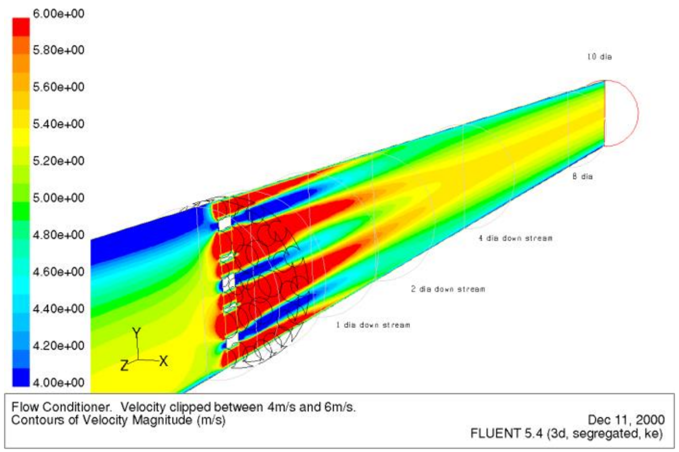
Swirl Example with 2 planes

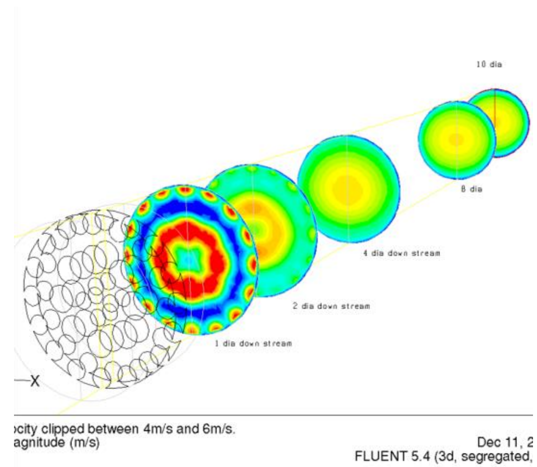
Cross velocities

- With cross planes (8 paths – still 4 chords) – cross velocities were addressed at the chord locations.
- Meter still requires assumptions about smoothness for it to not make errors (7 order polynomial). Industry recognizes this limitation – and generally requires flow conditioners

Some limitations when relying on just 4 chords/elevations

- Changes in Reynolds number – changes that "unmeasured" boundary layer – exposed the meter to unmeasured indication changes.
- Dependence upon flow conditioners – FCs create "lumpy" profiles – portions of which are not measured and not smooth





A clogged/fouled flow conditioner (debris or dirt) – changes the unmeasured parts of the flow fields (farther away… lessens the effects)

Consequences of Integration Approximations

- Stuck with just 4 chords (or 5) – liquid USM manufacturers must use correction curves and/or adaptive path weights to "fix" their native vulnerability to Reynolds Number changes (this correction is typically 2% to 6%). These "correction curves" depend upon:
  - Calibrating at the Reynolds Number to be used
  - A correction curve that requires exact knowledge of Reynolds Numbers (viscosity)
  - Requiring that the calibration uses identical upstream hydraulics to those in the field

  Otherwise… the meter's indication will "move" from what it had during calibration.

- What about reducing the bore?

  Effectively it puts a smaller meter throat into the line – moving to the "throat's" Reynolds number (by the ratio of the diameters). But the throat has the same Reynolds number vulnerabilities.

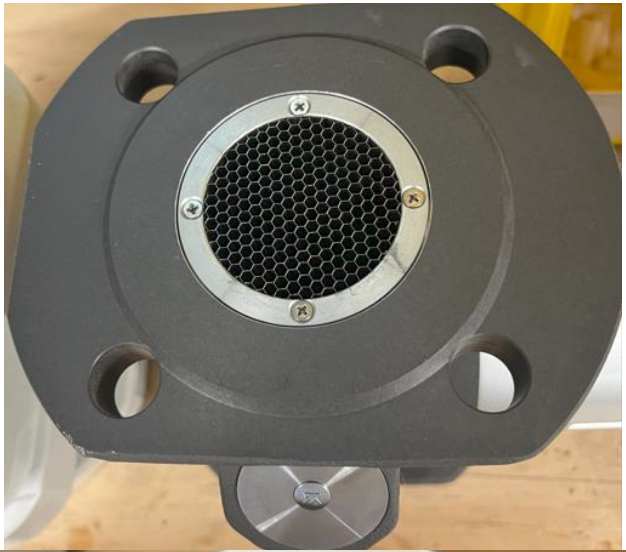
Consequences of Integration Approximations

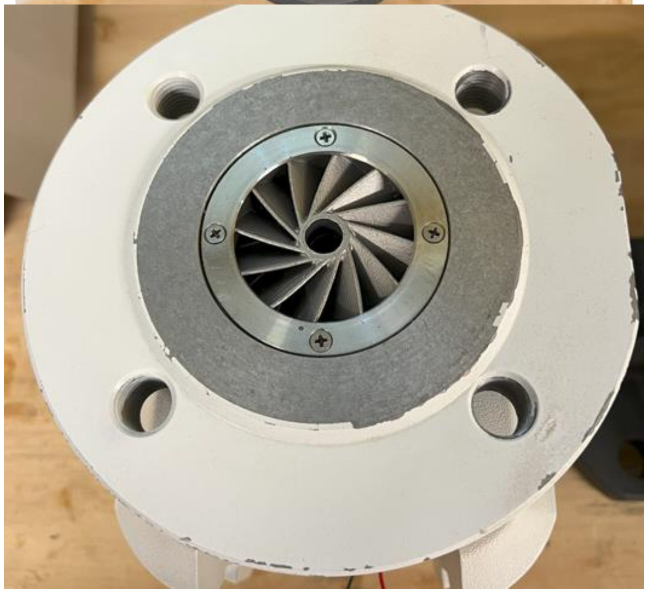
- USM Manufacturers must rely upon flow conditioners (and their cleanliness)
  - Requires clean flow conditioners … as a dirty flow conditioner changes the velocity profile in unmeasurable ways.
  - Next… Vigilant monitoring the velocity profile – to look out for “shape” changes that may indicate debris/dirt/blockage
  - (Fact – at 3D upstream… imperceptible lint on a flow conditioner changed an 8 path meter by over 1%).

Examples of USMs and their battle against upstream hydraulics

Some brands even try to use a single path/chord or 2 chords – and try to beat the flow into submission with built in flow conditioners…..

Just - Imagine the tremendous errors they make when it gets dirty or collects debris.





Favored methods of addressing what is not measured

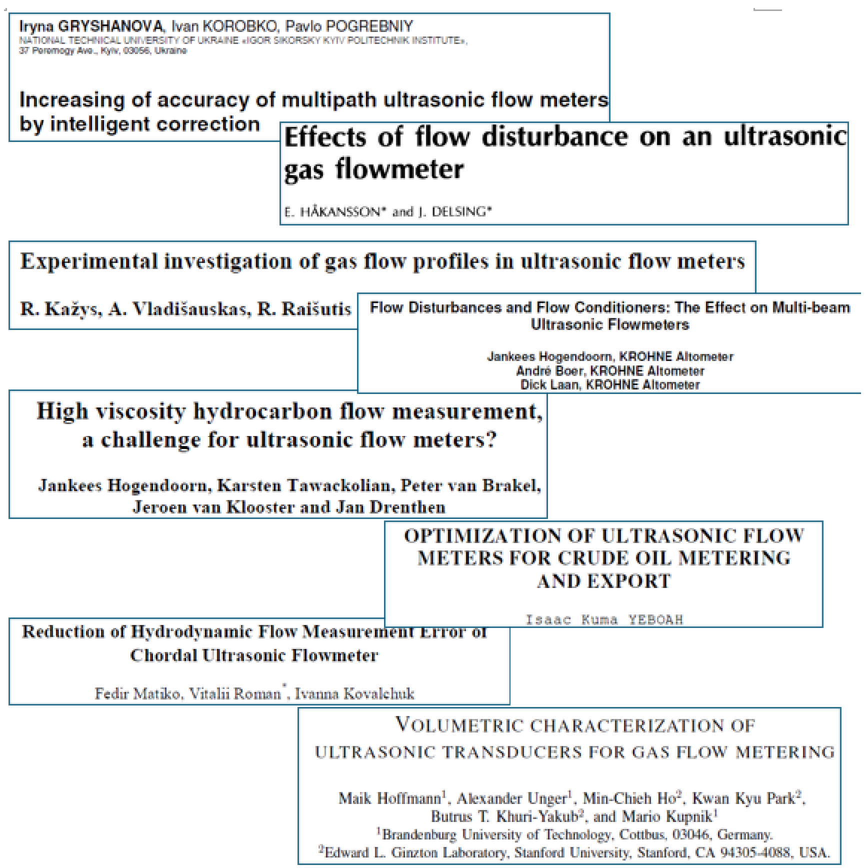
Current popular correction methods include (G = gas, L = Liquids):

- (G) Compare 4 chords vs. diameter path (“4+1”) – alarm if too big.
- (G) Compare 4 chords vs. a combination of same 4 chords and a diameter (“4+1”-ish) – alarm.
- (G) Alarm thresholds for profile deviations from calibration
- (G) “Condition based monitoring” software – to track velocity profile very carefully.
- (L) Careful calibration vs. Reynolds Number
- (L) “Figure out the Reynolds Number or its equivalent”

Favored methods of addressing what is not measured

Still… a rich topic for Academics (images of papers published on this topic)…

The challenge… how to account/verify/validate… what you don't measure.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Increasing of accuracy of multipath ultrasonic flow meters by intelligent correction

Effects of flow disturbance on an ultrasonic gas flowmeter

E. HÅKANSSON* and J. DELSING*

Experimental investigation of gas flow profiles in ultrasonic flow meters

R. Kažys, A. Vladišauskas, R. Raišutis

Flow Disturbances and Flow Conditioners: The Effect on Multi-beam Ultrasonic Flowmeters

Jankees Hogendoorn, KROHNE Altometer
André Boer, KROHNE Altometer
Dick Laan, KROHNE Altometer

High viscosity hydrocarbon flow measurement, a challenge for ultrasonic flow meters?

Jankees Hogendoorn, Karsten Tawackolian, Peter van Brakel, Jeroen van Klooster and Jan Drenthen

OPTIMIZATION OF ULTRASONIC FLOW METERS FOR CRUDE OIL METERING AND EXPORT

Isaac Kuma YEBOAH

Reduction of Hydrodynamic Flow Measurement Error of Chordal Ultrasonic Flowmeter

Fedir Matiko, Vitalii Roman*, Ivanna Kovalchuk

VOLUMETRIC CHARACTERIZATION OF ULTRASONIC TRANSDUCERS FOR GAS FLOW METERING

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The next step forward… measure the whole cross-section

What if (Patent submitted and pending) you were able to completely measure the flow field?

The design would allow:

- Near-perfect integration of the velocity profile
- Be able to measure that nasty area out at the boundary layer.
- You could install the meter – almost anywhere.

  .. And by demonstrating no flow indications errors in the most extreme hydraulics… we show how this meter is not sensitive to variations in the field.

- Flow conditioner "cleanliness" – not so important
- The only errors left are in the dimensions, electronics and 3D flow effects.

How to make a USM measure the whole cross-section?

- Need to create a flow meter body that has been designed to have many.. many paths – in our case… we use acoustic manifolds – just two manifolds hold all the paths.
- Helps if we make the paths dimensionally equivalent
  - Then paths/acoustics can be combined - as many or as few as desired
  - Use a manifold with an array of small identical piezoelectric transducers
- With identical transducers and identical acoustic paths (with regards to path length) – we can:
  - Create as many paths as we wish … in our case 22 paths OR 15 or 16 overlapping elevations/chords
  - Broadcast multiple paths simultaneously to integrate the velocity profile more quickly!

Wouldn't it be better to just to measure the velocity completely?

Our approach – rectangular cross-section.

With enough paths to completely measure the cross-section – it is a complete measurement and not an approximation.

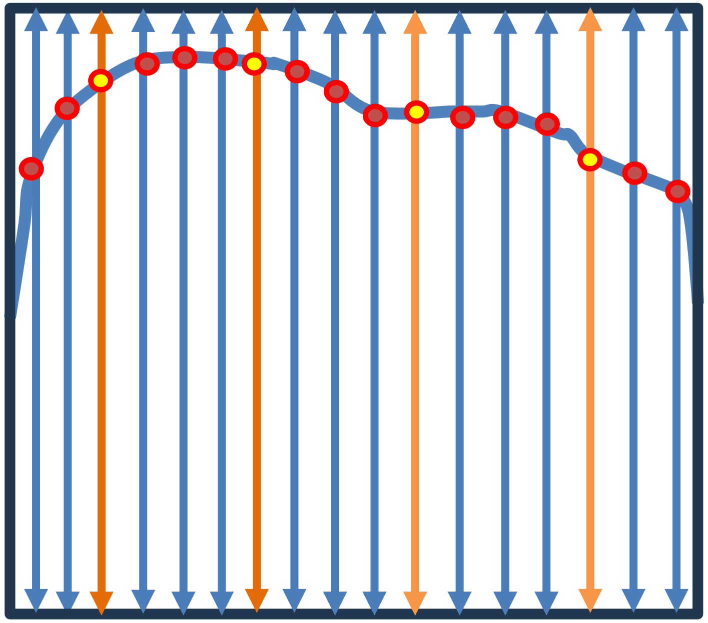
The meter does not depend upon a flow conditioner to make the flow field… "nice". (FC doesn't hurt it…)

The meter measures correctly over a wide range of Reynolds numbers (where profiles change… a lot):

Laminar <-> Transition <-> Turbulent

- For liquids (high viscosities)
- For gases (low pressures)

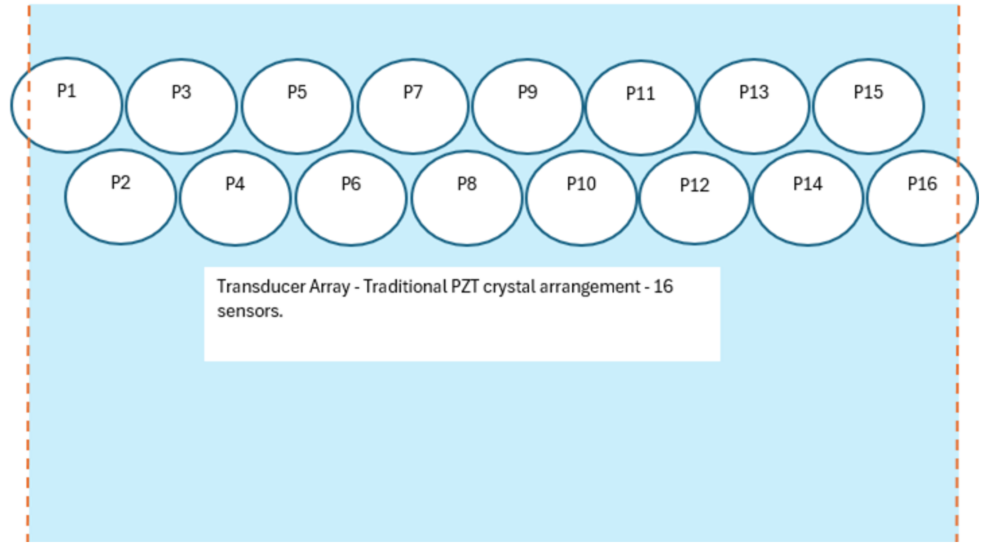
6 - inch meter – has 16 "wide chords" to completely cover cross section



Paths equally spaced and equally weighted by their area

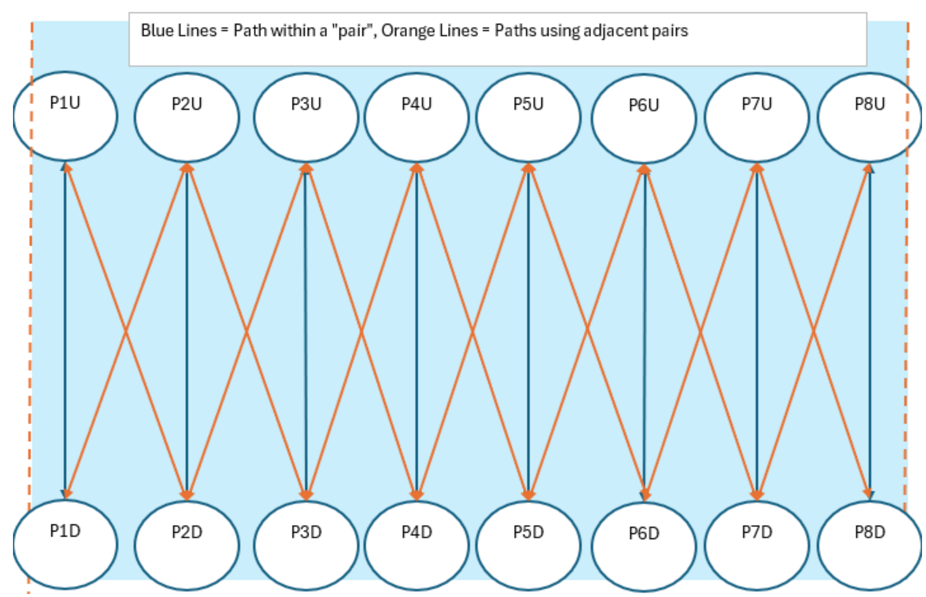
Make the meter "shape" accept as many "chords" as you want!

Method #1 – Squeeze in as many as possible



Method #2 – Construct paths that go between transducers.

(Nice side benefit – gains/performance can be determined on a per transducer basis … versus on a per "path" basis)

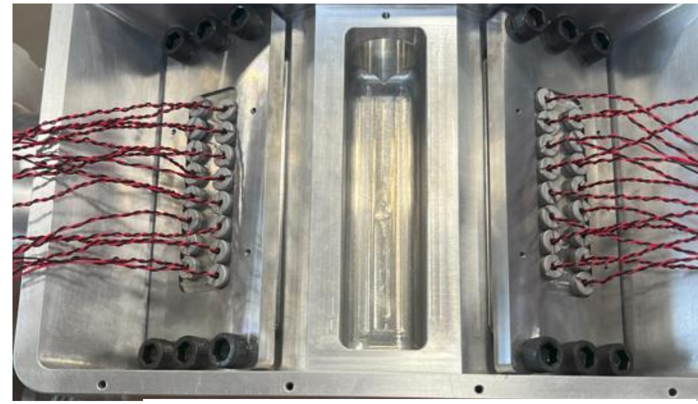


Flow Data – to Demonstrate Performance

Complete Integration - iSonic-8X-L3G and iSonic-8X-L3L

6 inch L3 – Off to Alden

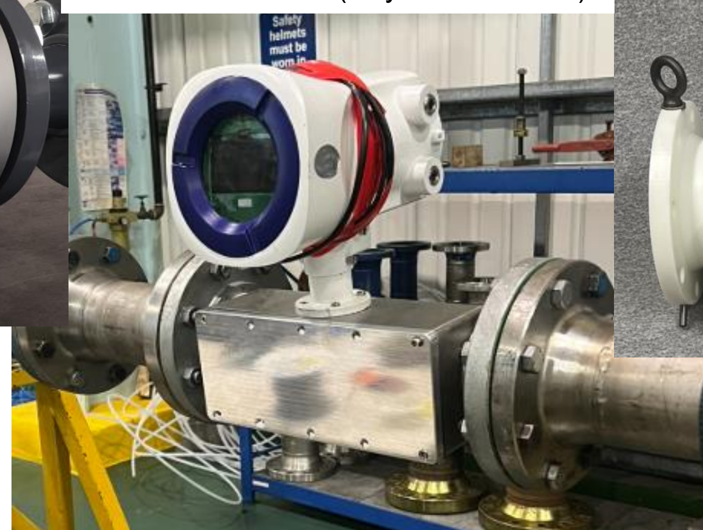
6 inch L3 – 16 chords during assembly



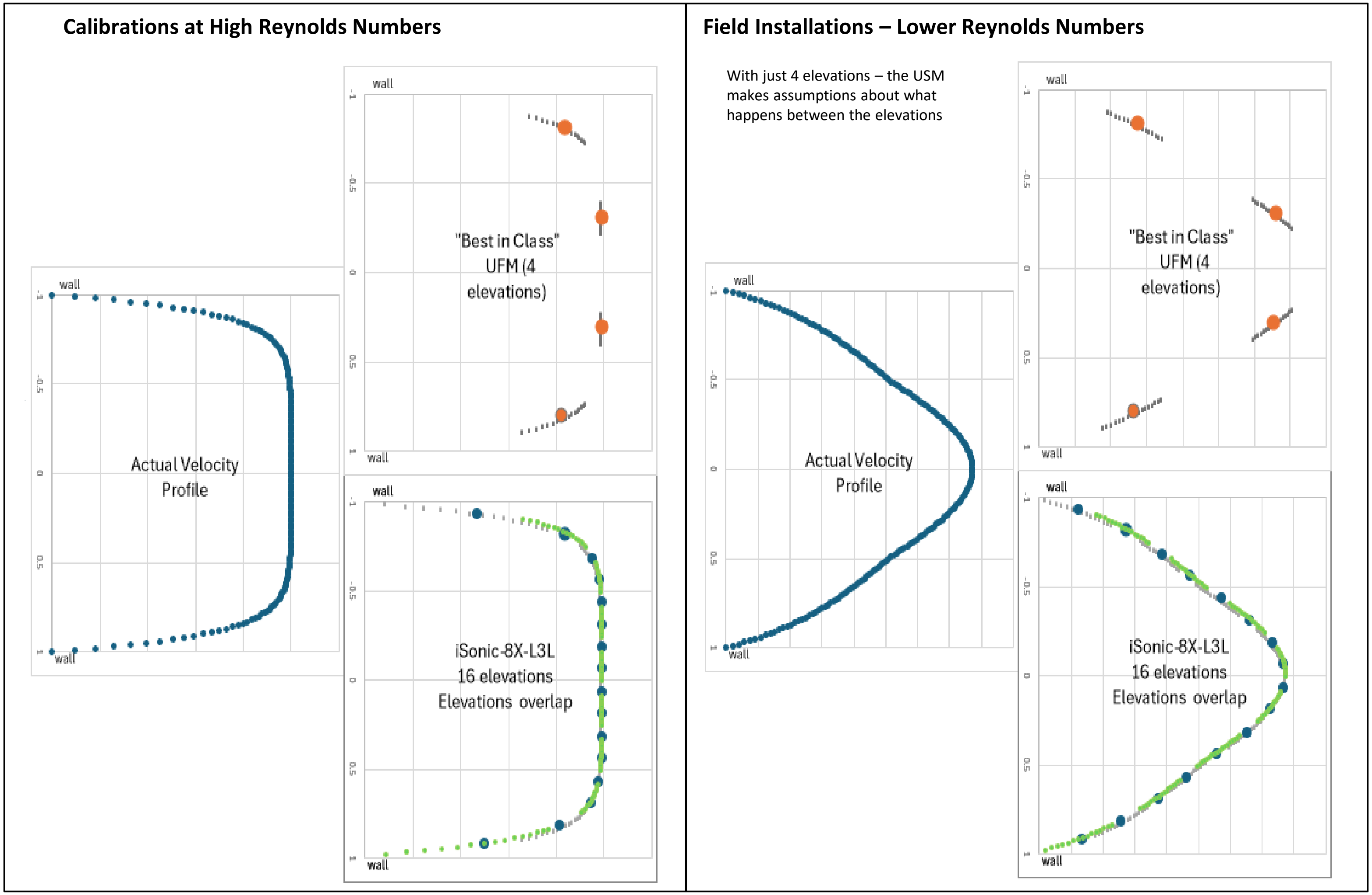
6 inch L3 – Demo Meter

2 inch L3 – at Insight Metering Designs flow loop

4 inch L3 – at NEL (Reynolds number)

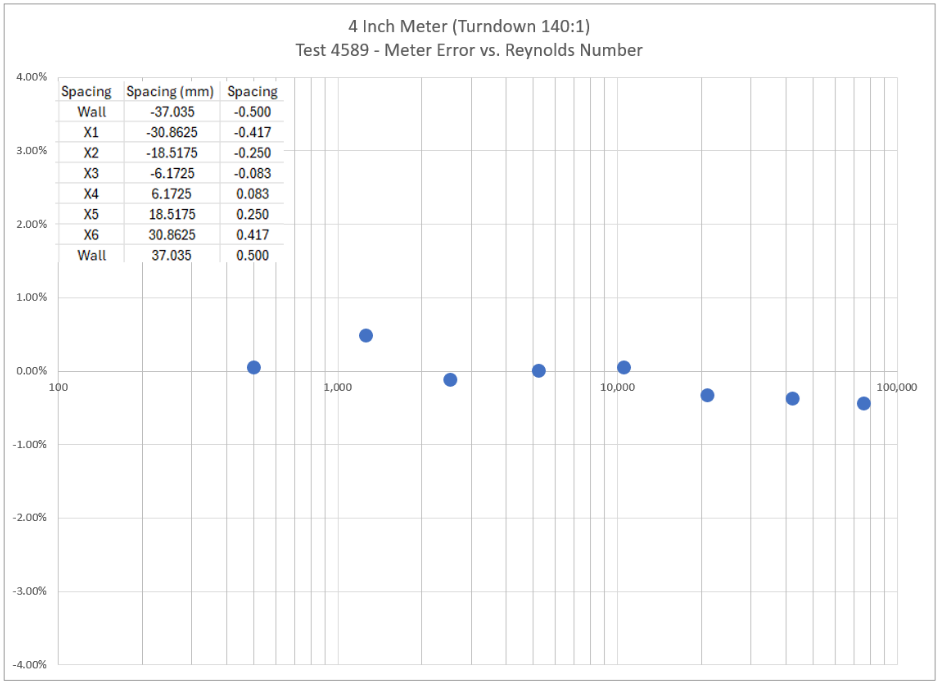


Native Performance Comparison
L3 vs. Gaussian Quadrature (4 elevations)



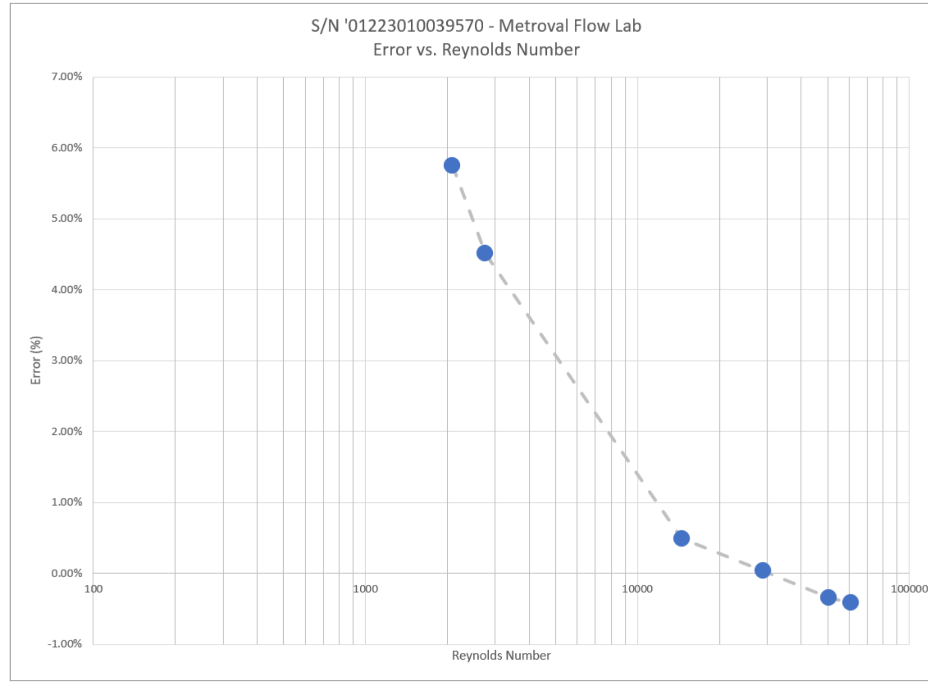
Native Performance Comparison
L3 vs. Gaussian Quadrature (4 elevations)

4 Inch L3 (@ NEL)
Reynolds number (X axis)



Spacing	Spacing (mm)	Spacing
Wall	-37.035	-0.500
X1	-30.8625	-0.417
X2	-18.5175	-0.250
X3	-6.1725	-0.083
X4	6.1725	0.083
X5	18.5175	0.250
X6	30.8625	0.417
Wall	37.035	0.500

6 Inch – Typical USM 8 paths with 4 Elevations (Liquids at Metroval Lab)
Reynolds number (X axis)



Prototype – did not measure
the last 6 mm out of 100 mm

Demonstration Tests - Verdantas/Alden Labs (June 2- June 5)

Verdantas (Holden Massachusetts)

Hot water (40-43 deg C)

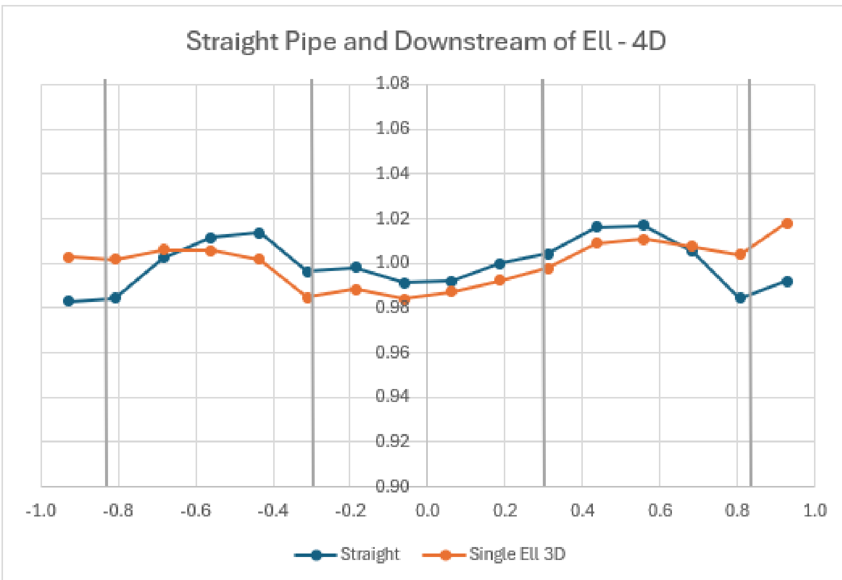
Weigh Tank (1,000 lbs. up to 10,000 lbs.).

Baseline 7 flow rates

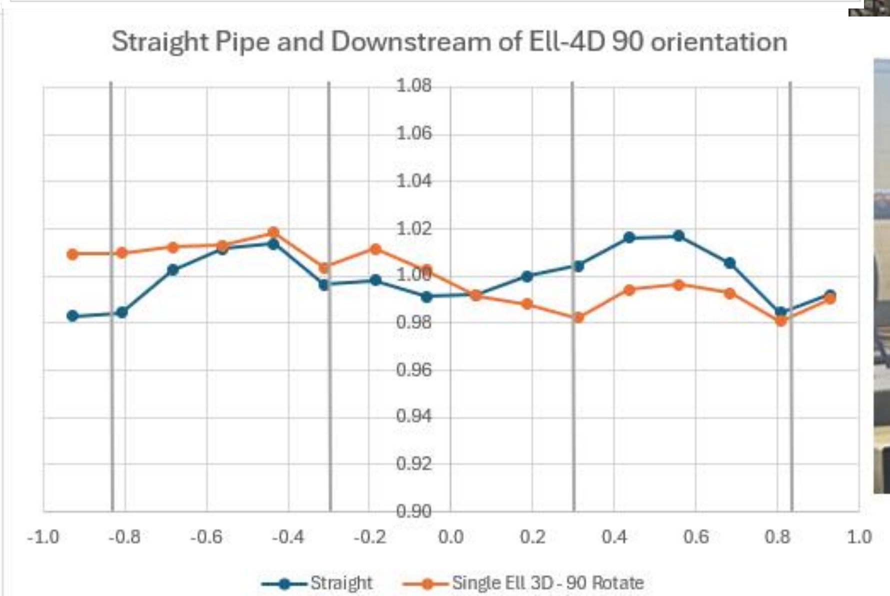
Disturbance tests per R137 (100%, 40% and 25%)

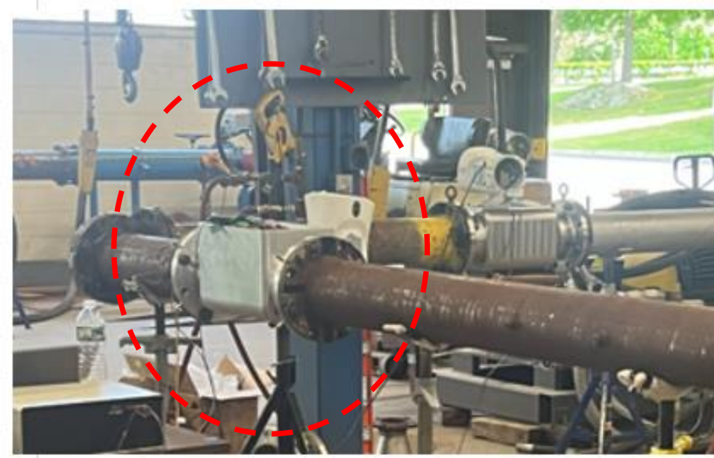
Single Elbow	Meter 1	Straight Pipe
		3.4 D Downstream of Single Ell - Measurement in plane
		3.4 D Downstream of Single Ell - Measurement Perpendicular Plane
		0 D Downstream of Single Ell - Measurement in plane
		0 D Downstream of Single Ell - Measurement Perpendicular Plane
DBOOP	Meter 2	Straight Pipe
		3.4 D Downstream of DBOOP - Measurement in plane
		3.4 D Downstream of DBOOP - Measurement Perpendicular Plane
		0 D Downstream of DBOOP - Measurement in plane
		0 D Downstream of DBOOP - Measurement Perpendicular Plane
	Meter 3	10 D Downstream of Single Ell
		Straight Pipe
		Straight Pipe
		Straight Pipe
		Straight Pipe

6 Inch Meter #1 Straight vs. Downstream 3.5 D Single Elbow all data – all flow rates +/- 0.12%

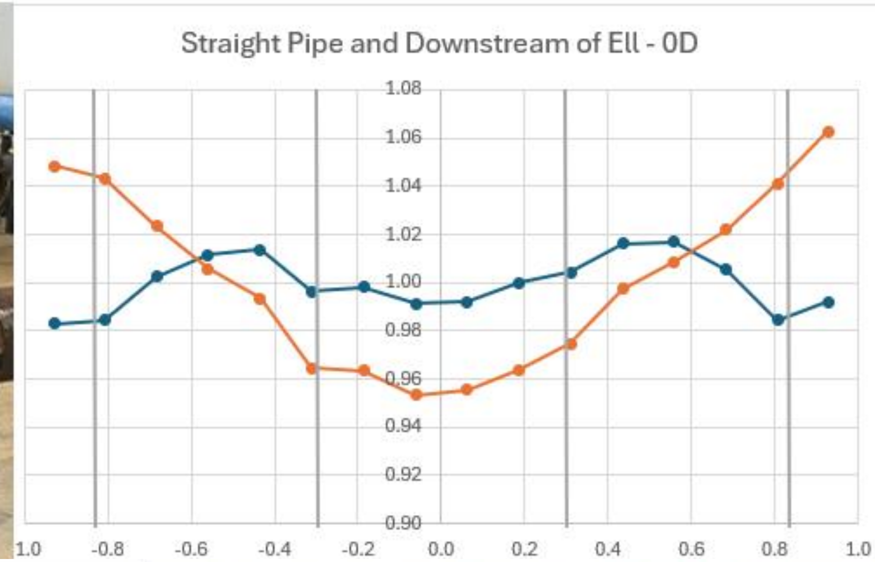


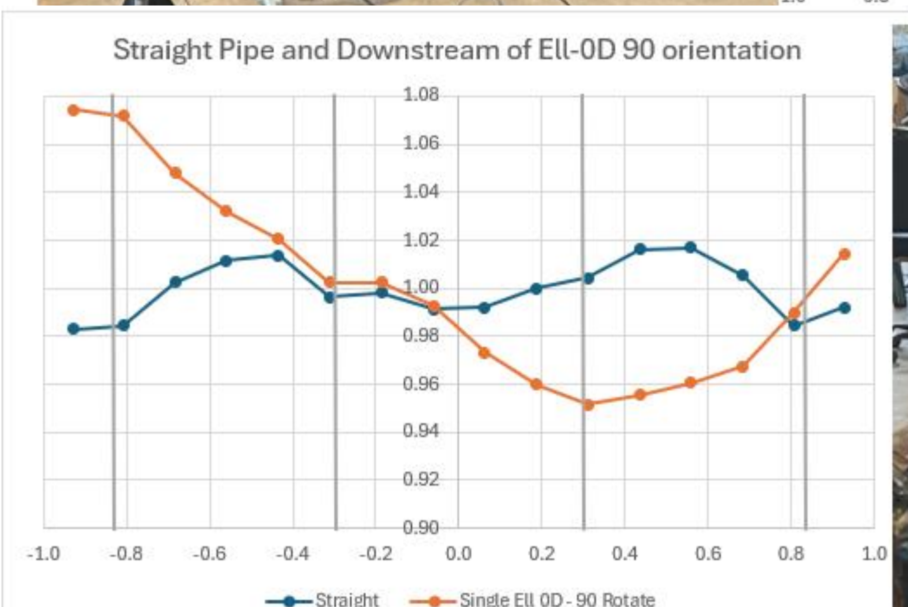
6 inch Sch 40 – 150# flanges





6 Inch Meter #1 Straight vs. Downstream 0 D Single Elbow all data – all flow rates +/- 0.12%

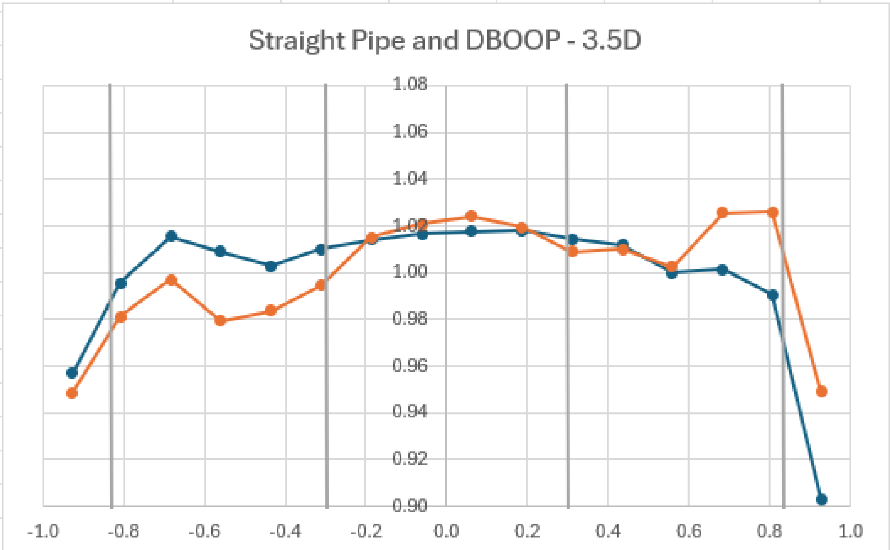




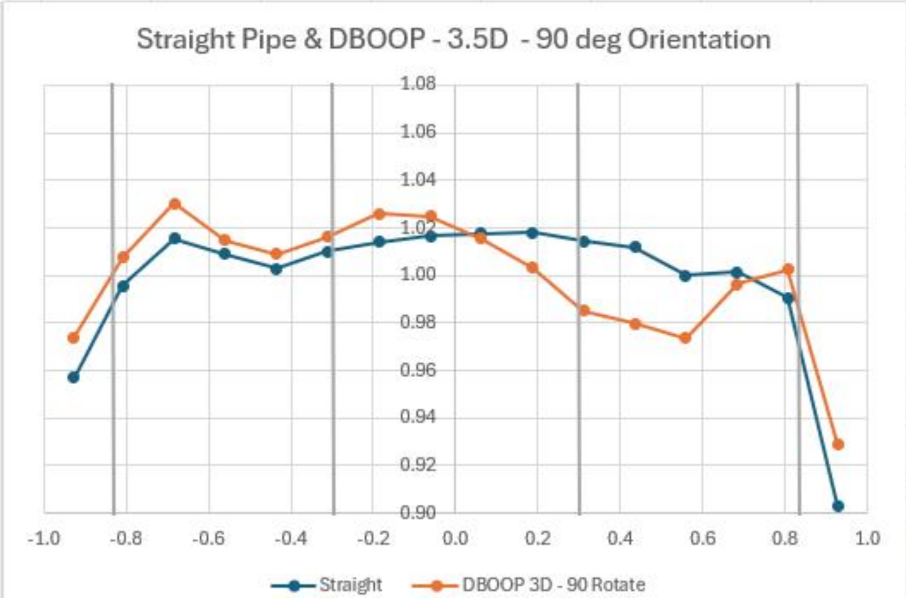
6 Inch Meter #2 Straight vs. Downstream 3.5D DBOOP all data – all flow rates +/- 0.15%

6 inch Sch 40 – 150# flanges

Measure perpendicular to last elbow

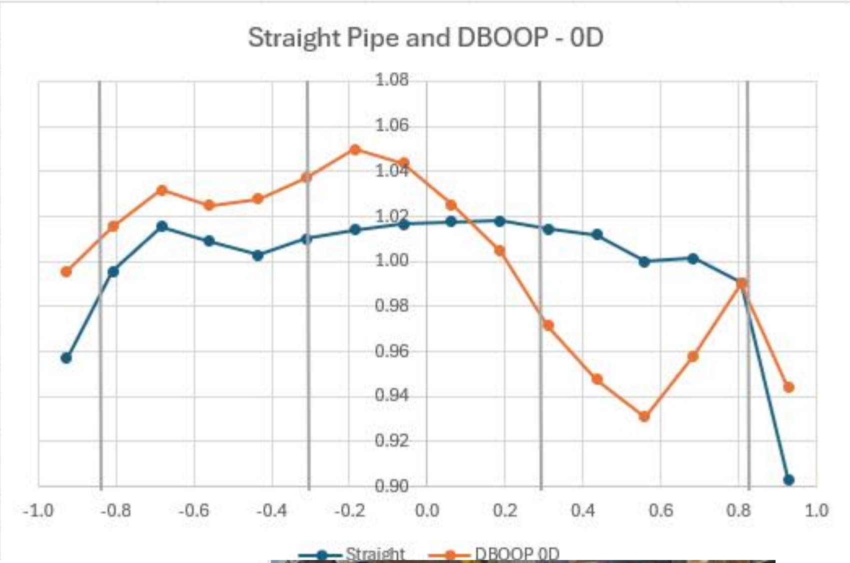


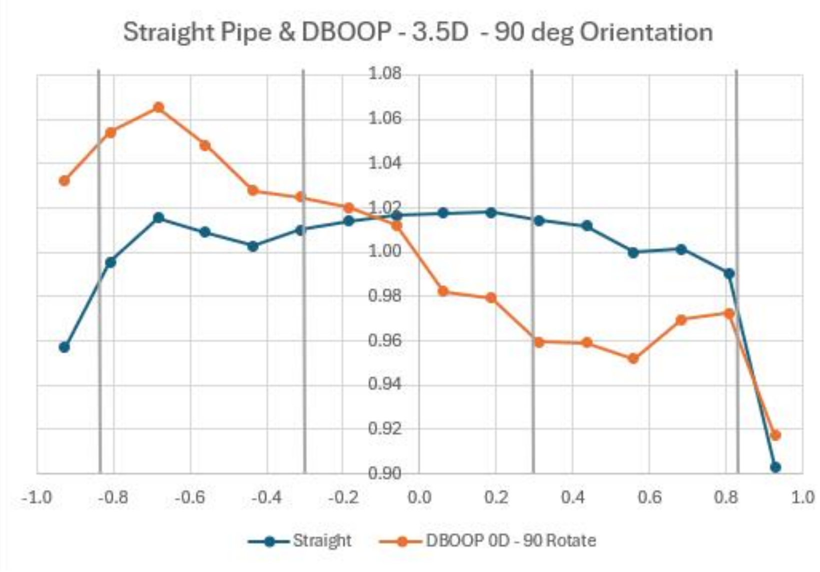
Measure in plane of last elbow



6 Inch Meter #2 Straight vs. Downstream 0 D DBOOP

Difference from straight pipe all data – all flow rates +/- 0.15%



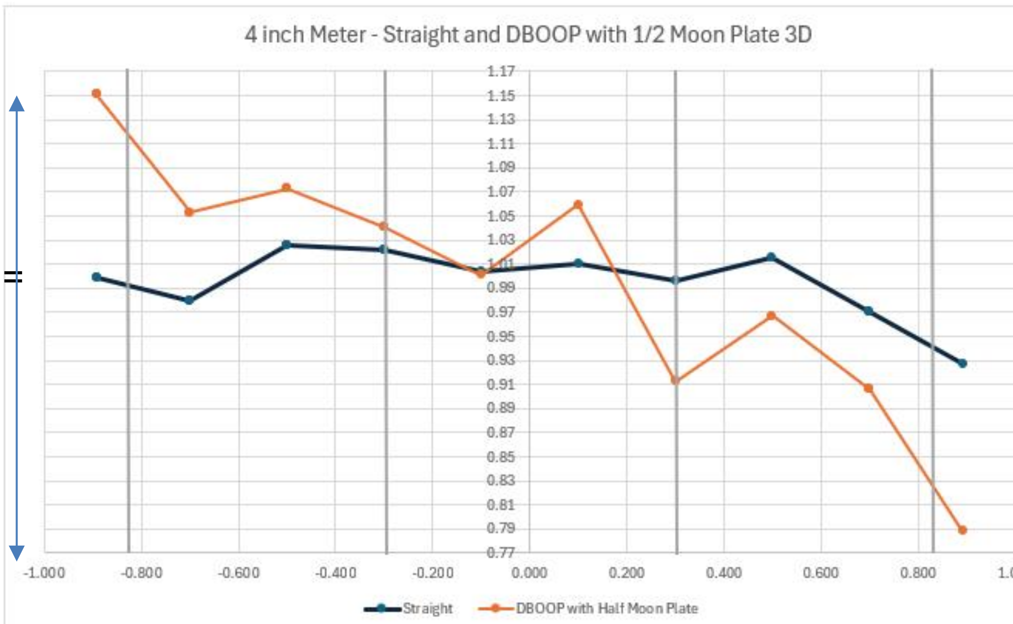


Scale = 18%

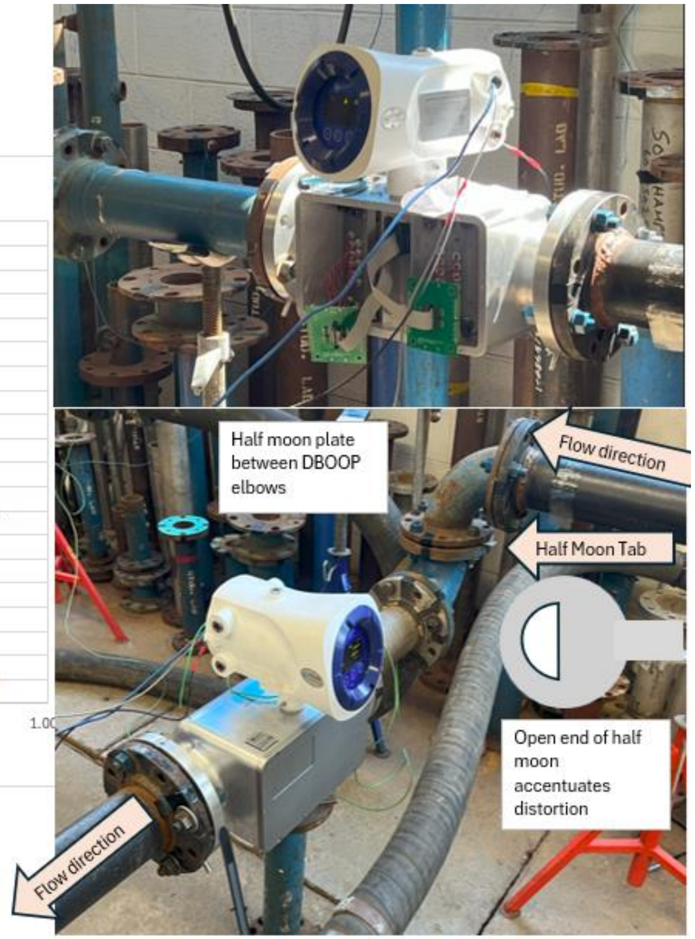
4 inch Meter Straight vs. Downstream 3D DBOOP PLUS Half Moon Plate between the Non-Planar elbows

Differences from Straight - All data – all flow rates +/- 0.25%

Scale = 40% Wow!



Path velocities change 16%/inch

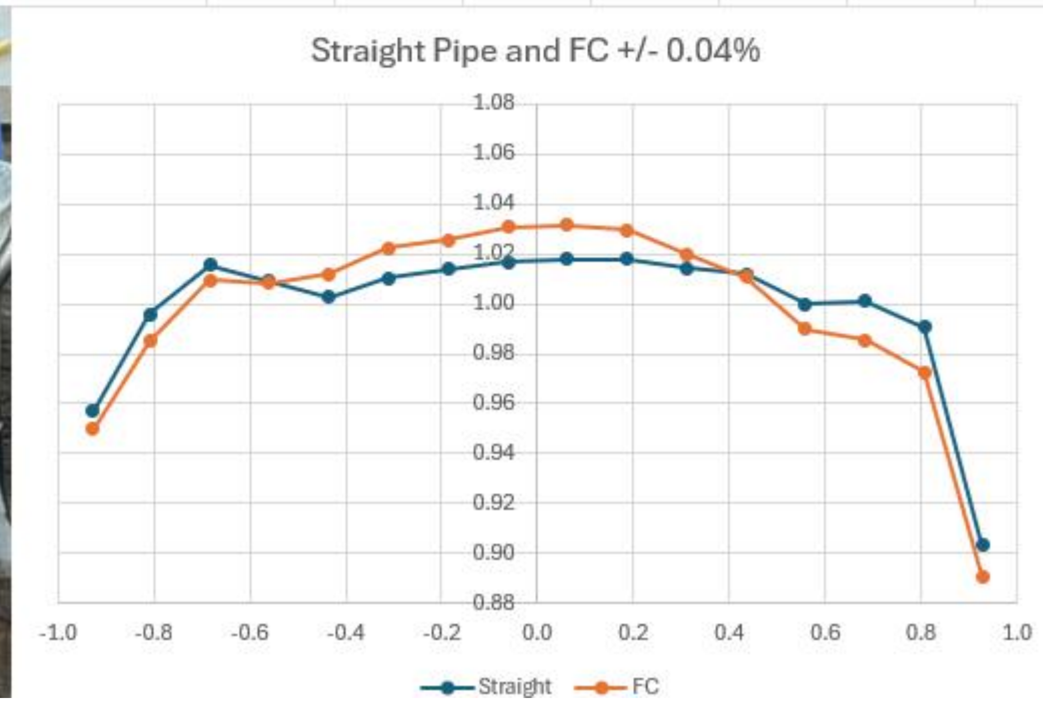


6 inch Meter #2 Straight vs. Downstream FC and FC with Blockage

Flow Conditioner

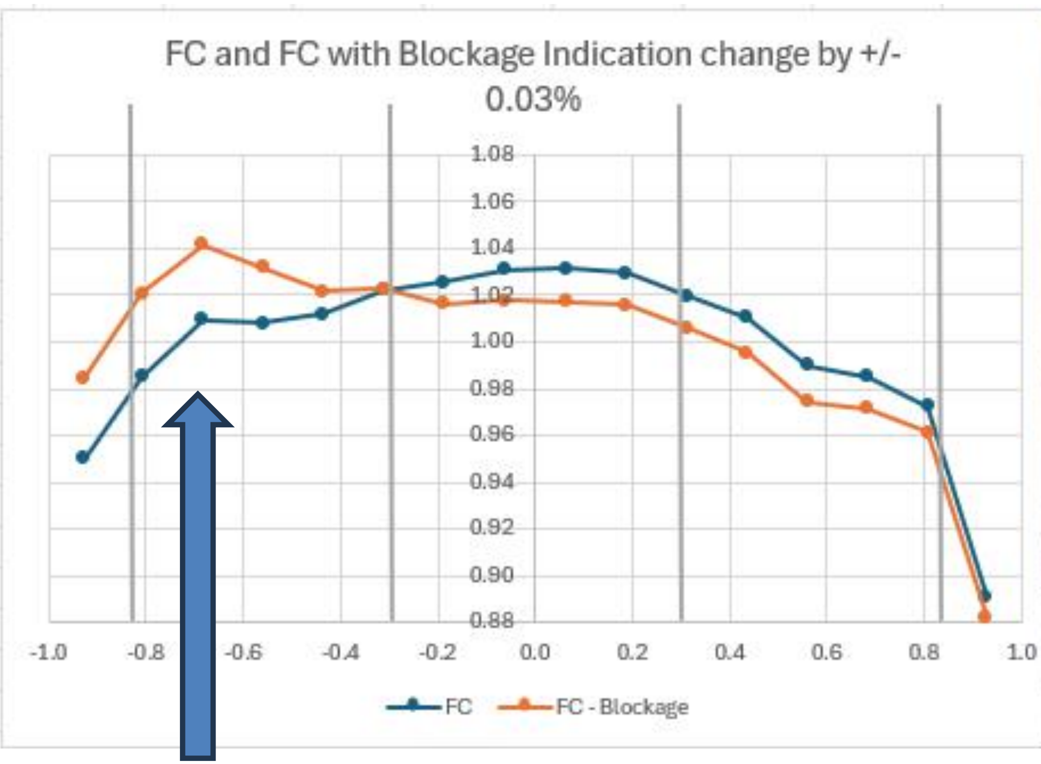
6 inch Meter #2 Straight vs. Downstream FC and FC with Blockage

Straight to FC - All data – all flow rates +/- 0.04%



6 inch Meter #2 Straight vs. Downstream FC and FC with Blockage

FC to FC with Blockage Indication change +/-0.03%

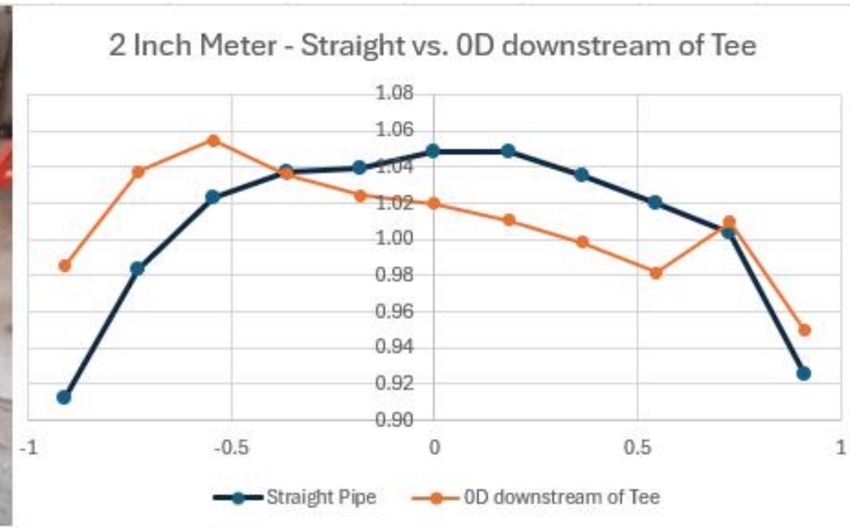


Coandă effect

Blockage at Bottom of pipe

2 inch Meter Straight vs. 0D Downstream Tee

All data all flow rates +/- 0.25
2 inch meter has only 11 chords (6 direct and 10 “diagonal” paths) – so.. Not as tightly packed measurements



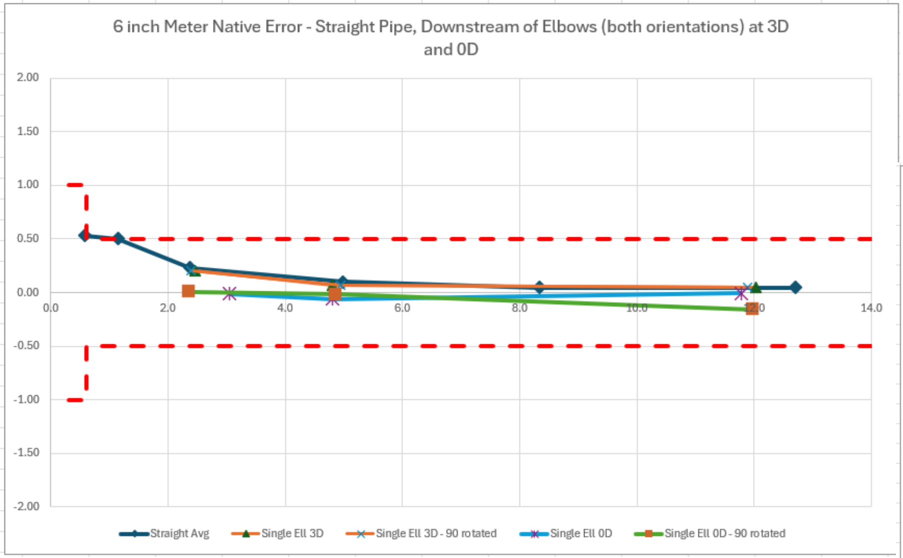
Disturbance Testing Summary – 6 inch and 4 Inch Meters

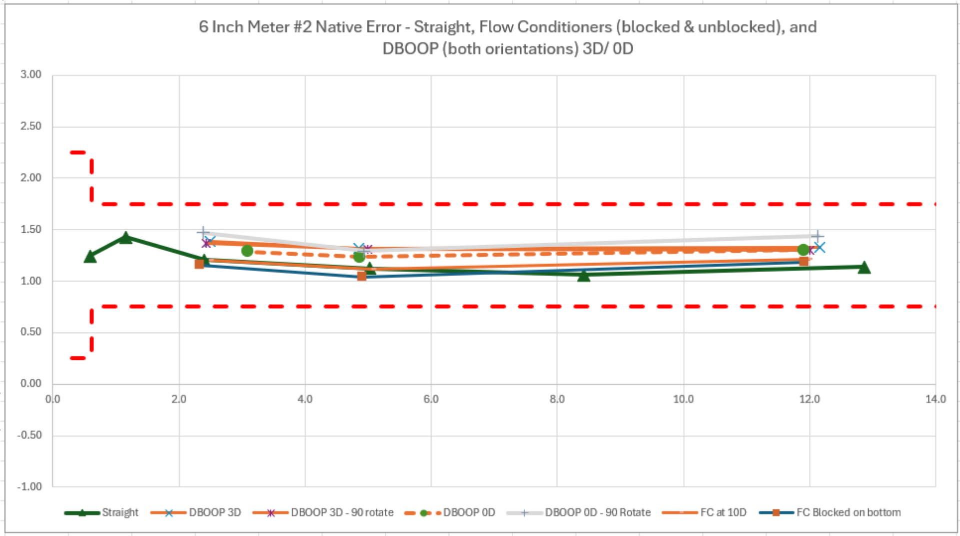
Per OIML R137 – Disturbance tests run at 100% Qmax, 40% and 25%

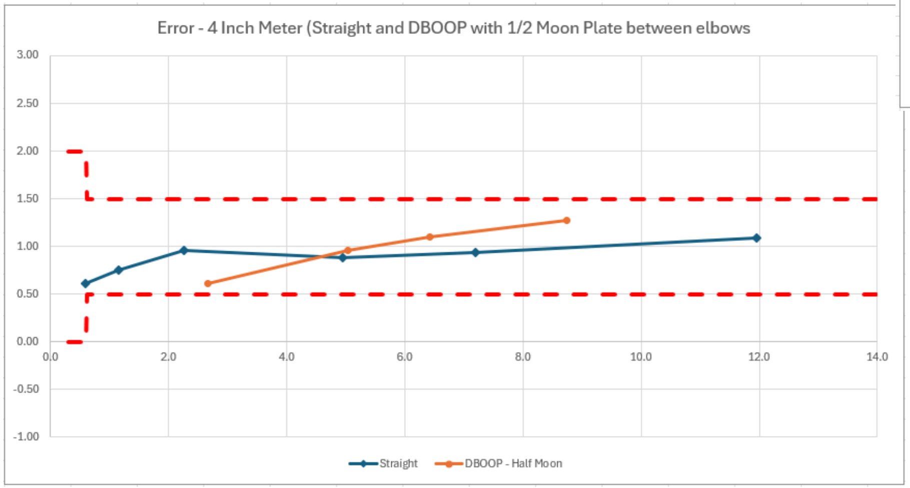
Disturbance Testing Summary								
Straight Pipe 6 inch	FC Upstream 6 inch	FC Upstream with blockage 6 inch	3D from Single Elbow (0 degree and 90 degree Orientation) 6 inch	0D from Single Elbow (0 degree and 90 degree Orientation) 6 inch	3D from Double Out of Plane Elbow Elbow (0 degree and 90 degree Orientation) 6 inch	0D from Double Out of Plane Elbow Elbow (0 degree and 90 degree Orientation) 6 inch	0D from Double Out of Plane Elbow Elbow (0 degree and 90 degree Orientation) 4 inch meter	All data - All flow rates
X	X							+/-0.04%
	X	X						+/-0.03%
X	X	X	X					+/-0.12%
X	X	X	X	X				+/-0.12%
X	X	X	X	X	X			+/-0.15%
X	X	X	X	X	X	X		+/-0.15%
X	X	X	X	X	X	X	X	+/-0.25%

Disturbance Testing Summary – 6 inch and 4 Inch Meters

Per OIML R137 – Disturbance tests run at 100% Qmax, 40% and 25%







Disturbance Testing Summary – 1, 2, 3 inch

Private lab, Coriolis reference.

Disturbers to ISO 4064-2:2014 (Annex I).

2” meter, 11 chords

Disturbance	Deviation from baseline
25% blockage 0D	0.21% ± 0.18%
25% blockage 3D	0.36% ± 0.26%
Swirl 0D	-0.06% ± 0.52%
Swirl 3D	0.16% ± 0.40%

3” meter, 11 chords

Disturbance	Deviation from baseline
25% blockage 0D	-0.04% ± 0.24%
25% blockage 3D	-0.03% ± 0.17%
25% blockage 0D at 90 degrees	0.20% ± 0.60%
25% blockage 3D at 90 degrees	-0.18% ± 0.43%
Swirl 0D	-0.78% ± 0.27%
Swirl 3D	-0.49% ± 0.30%

≥7 test points, including lower flows ~100mm/s

1” meter, 5 chords

Disturbance	Deviation from baseline
25% blockage 0D	0.01% ± 0.81%
25% blockage 3D	-0.02% ± 0.32%
25% blockage 0D at 90 degrees	0.17% ± 0.78%
25% blockage 3D at 90 degrees	0.09% ± 0.32%
Swirl 0D	-0.03% ± 0.81%
Swirl 3D	-0.09% ± 0.77%
1.5” pipe inlet	-0.18% ± 0.19%

Conclusions - Performance

- Disturbance Tests: Demonstrated that 100% flow field measurement methodology is not sensitive to upstream disturbances - even some extremely severe disturbances.
- By extension – a meter that measures 100% of the flow field is not sensitive to flow conditioner plugging (though it may tell you when it happens) – improves maintainability as the flow conditioner does not need to be cleaned OR to any of the many possible things that can occur in the field.
- Upstream conditions are not an application concern.
- Disturbance Test Profiles would never be able to integrated by four chords.
- Disturbance Tests: Demonstrated that by measuring 100% - you can validate the measurement is correct.
- Reynolds Number Tests: Demonstrate that even a prototype meter – is far more NATIVELY linear from RN = 1,500 to 150,000 – will not require “software” to straighten a noodle of errors.

What Next? Hang On – this is Fun!

This… is … EXCITING … excellent performance - so much is happening… and it is all fun and great. Upcoming events:

- Prover Demo Tests: (6 inch meter) with compact provers with our partner Metroval – ONGOING.
- Repeat Wide Reynolds Tests: Reynolds Numbers range (3 fluids) at Metroval – ONGOING
- LACT Demo Test: December (either 3 inch and/or 4 inch)
- Gas L3 Meter: November (6 inch) at TCC/CEESI
- Liquid CO2 test: NEL 2026

Insight is excited as to what is possible when you “just measure the whole thing”