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Surface Pressure Measurements on a Free-Flying Cone at Mach 7 using Pressure Sensitive Paint

Christopher Wheeler[1], Andrew Hysop[1], Joao Vieira[1], Laurent Le Page[1], Mark K. Quinn[2], Nafiz H.K. Chowdhury[1] and Luke J. Doherty[1]

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Scope:

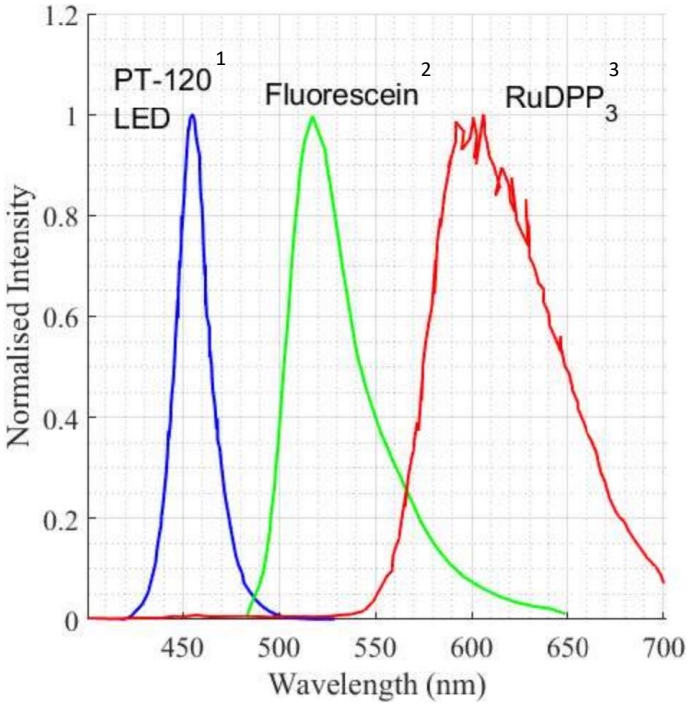
- Introduction
- In-house Binary Formulation
- High Density Tunnel (HDT)
  - Experimental Setup
  - Processing
  - Results
- Summary

Introduction:

- Measuring aerodynamic phenomena experimentally is required to validate computational models and understand efficiency of flight.
- Realistic force measurement in short-duration hypersonic test facilities is non-trivial and can affect results.
- Free-flight can provide a more accurate testing regime.
- PSP offers a non-intrusive, high-quality method of obtaining surface pressure measurements.
- **Aim: Assess feasibility of using a cost-effective, binary-PSP on a free-flying model in the University of Oxford High Density Tunnel (HDT)**

In-house Binary Formulation:

Based off Recipe 3 of *Fast PSP (PC-PSP)* from *PRESSURE AND TEMPERATURE SENSITIVE PAINTS, Liu and Sullivan, 2021*



Data from: [1], [2] and [3]

Components:

Pressure Luminophore:	$RuDPP_3$
Reference Luminophore:	Fluorescein
Polymer Binder:	RTV-118 Silicone
Ceramic Binder:	TiO_2, 32 nm nanoparticles
Solvents:	Toluene, DCM

High Density Tunnel (HDT) Experimental Setup:

HDT: Heated Ludwig tube mode.

- 17.4 m long
- 6” barrel
- 350 mm exit diameter (Mach 7 nozzle)

Test Flow Condition

	Parameter	Units	Value	Uncertainty
Measured	p_0	kPa	3375	±7
Assumed	p_p/p_0	-	0.0149	±0.0002
	T_0	K	555	±15
Calculated Freestream	M	-	7.05	±0.02
	p	Pa	780	±16
	T	K	51	±1.4
	u_x	m/s	1006	±14
	Re_u	10^6/m	16.5	±0.8

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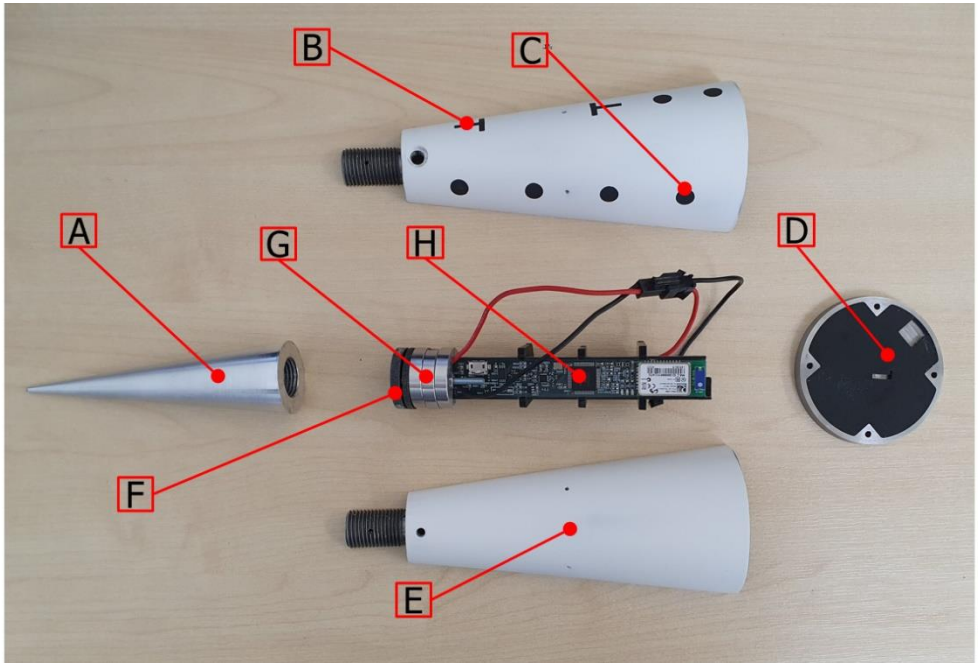
High Density Tunnel (HDT) - Experimental Setup:

7° half angle cone



A. Aluminium nose
B. Electromagnetic alignment marker
C. Optical Tracking Dots
D. Steel rear with 3D printed insert
E. Steel cone half
F. 3D printed DAQ mount
G. Tungsten ballast
H. DAQ

Hyslop *et al.* (2022)
doi:10.2514/6. 2022-1324

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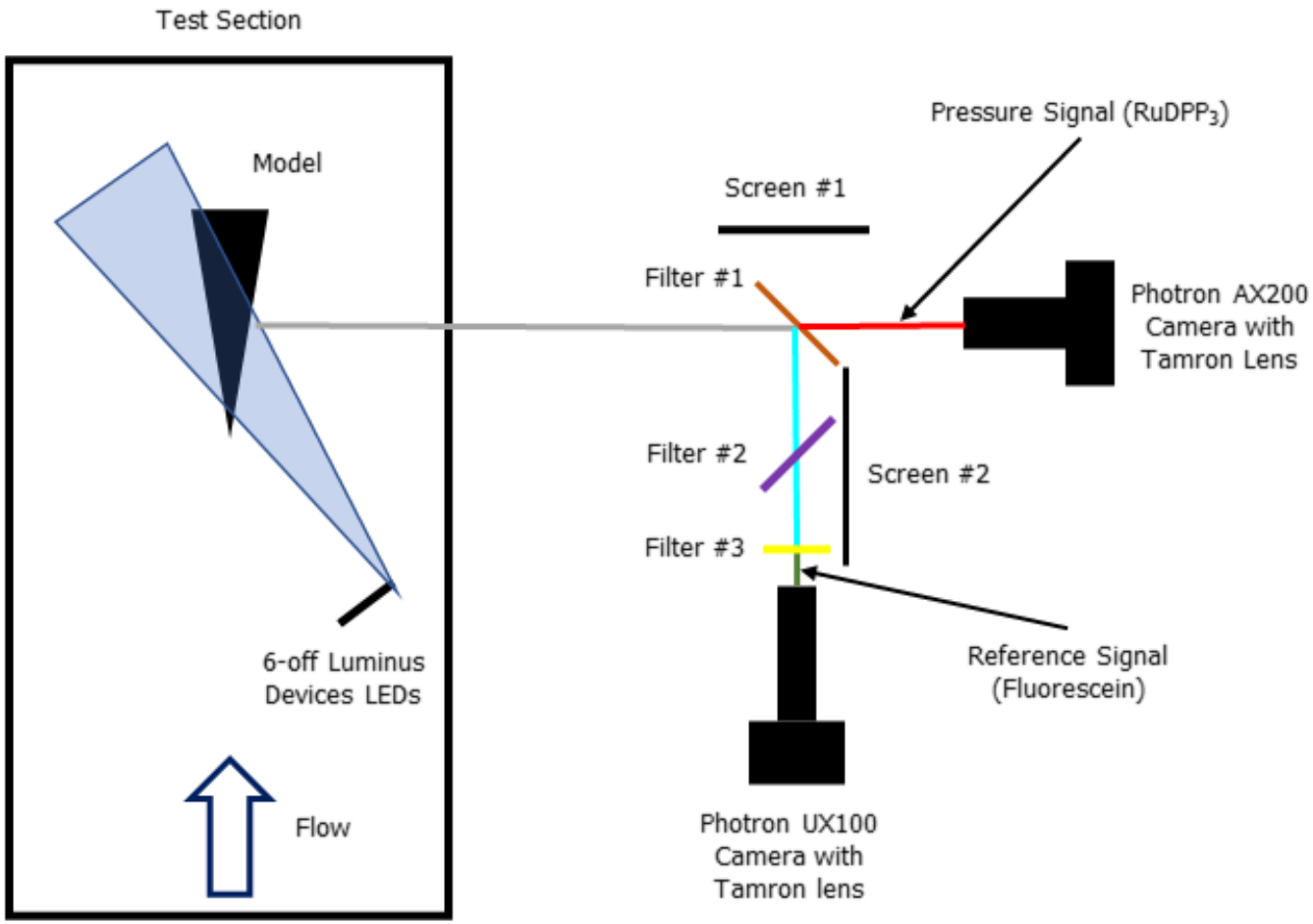
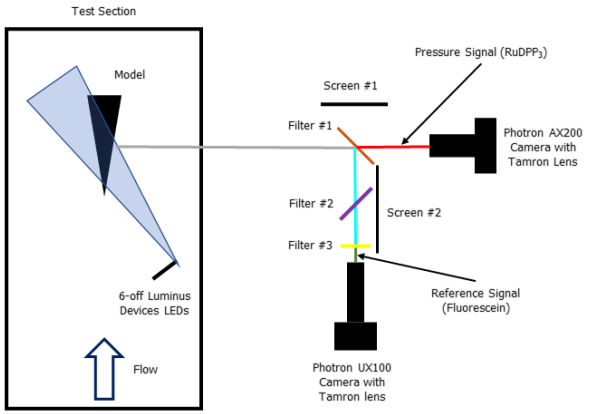
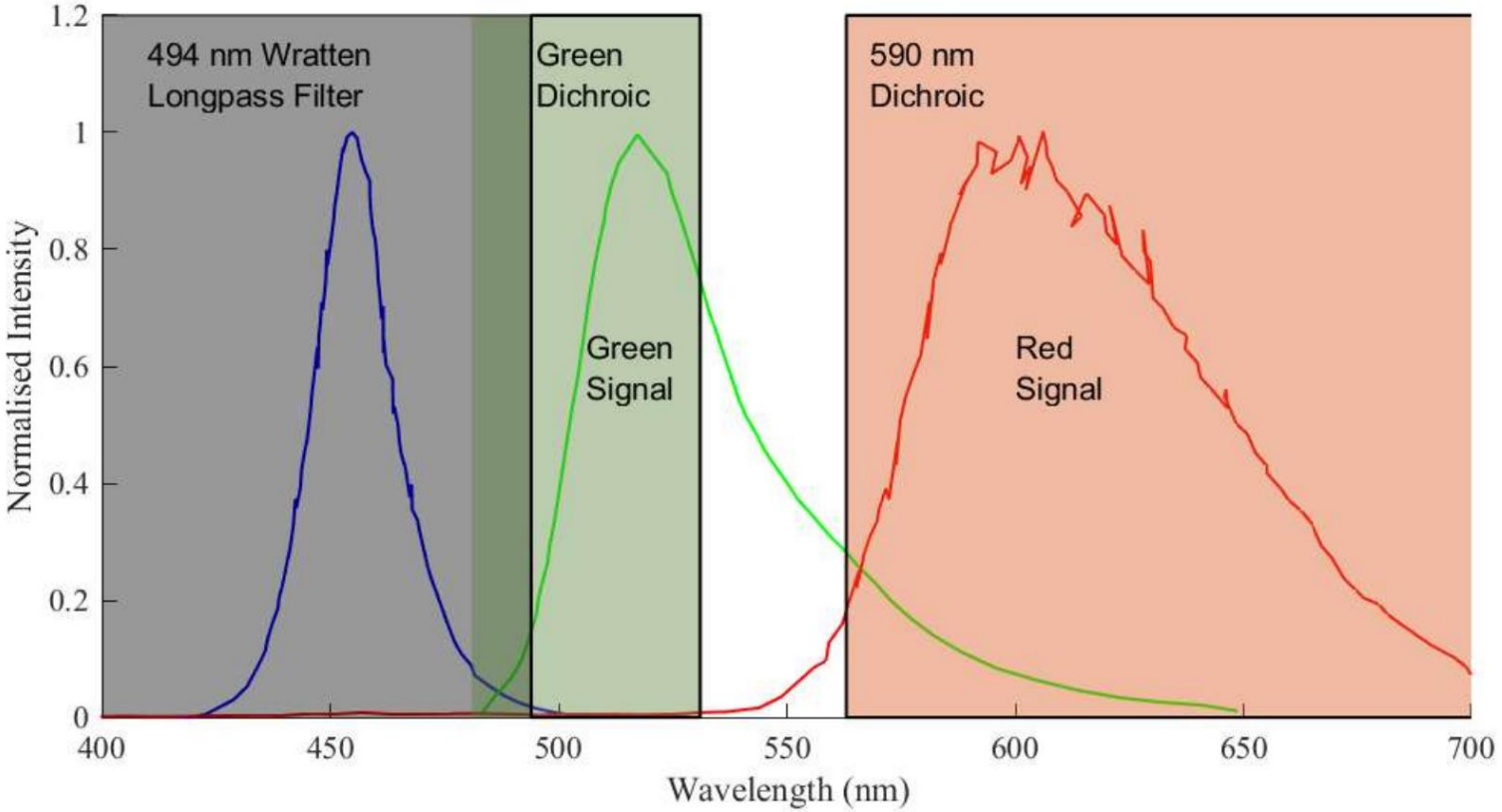
High Density Tunnel (HDT) - Experimental Setup:



High Density Tunnel (HDT) - Experimental Setup:





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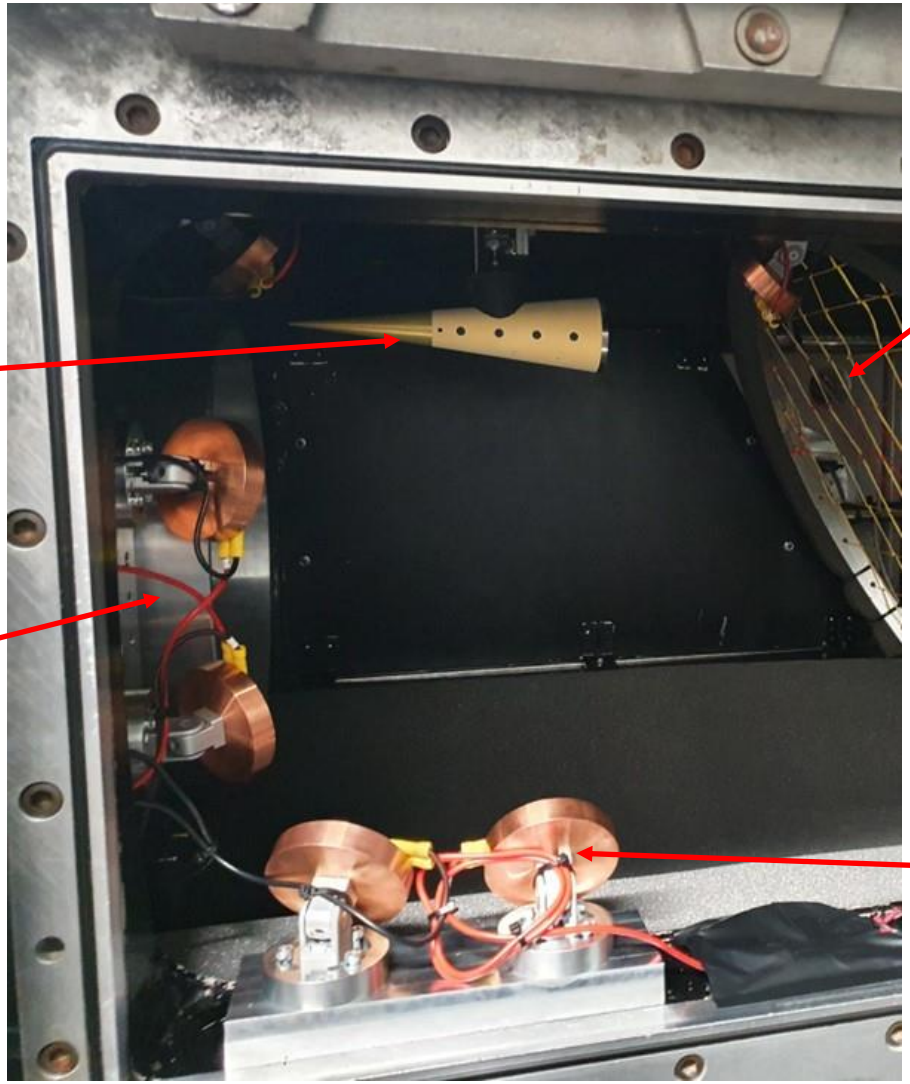
High Density Tunnel (HDT) - Experimental Setup:



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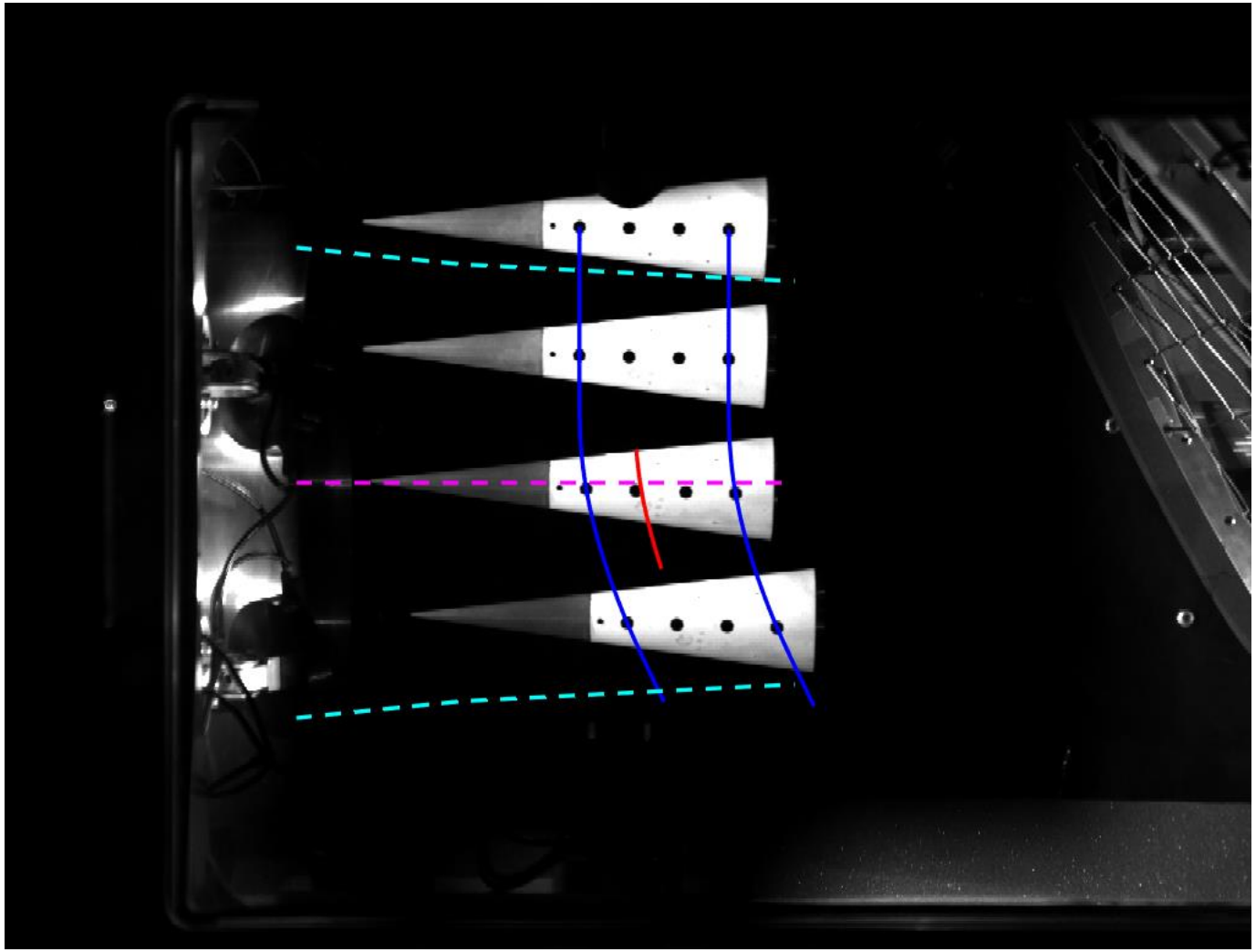
High Density Tunnel (HDT) - Processing:



Detected Circle Centre Points

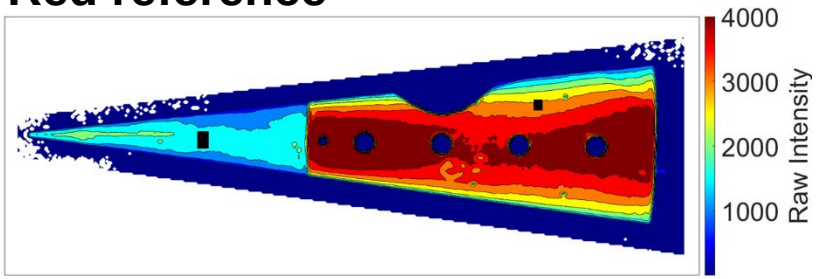
Calculated Centre of Mass

Facility Nozzle Centreline

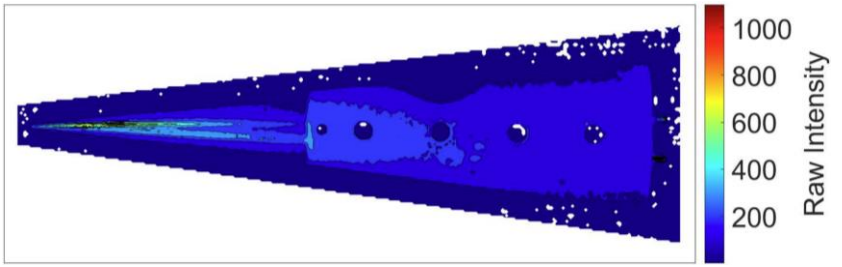
Core-flow Extent

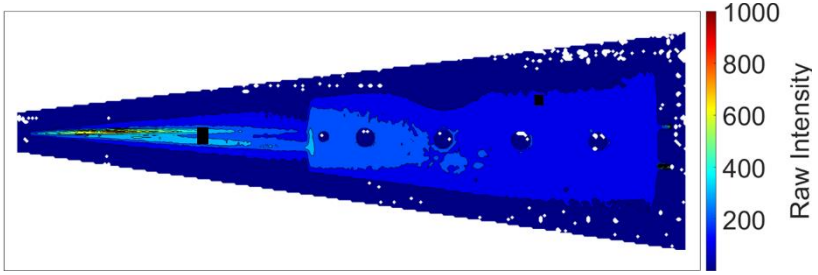
High Density Tunnel (HDT) - Processing:

Red reference

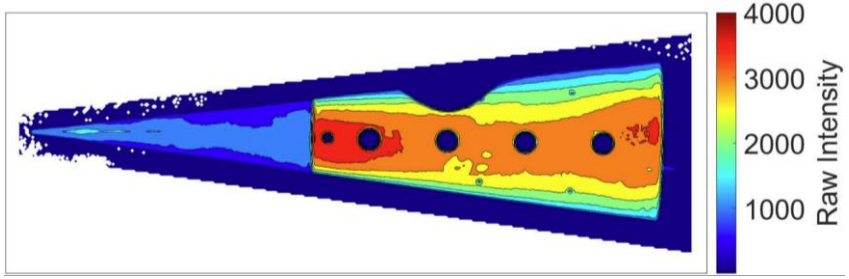


Green



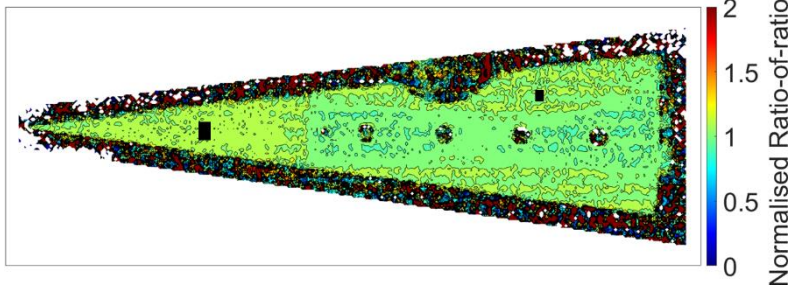


Green reference



Red

$$\frac{\overline{I_{ref}}}{\bar{I}} = \frac{\frac{I_{p,\mathrm{ref}}}{I_p}}{\frac{I_{r,\mathrm{ref}}}{I_r}}$$



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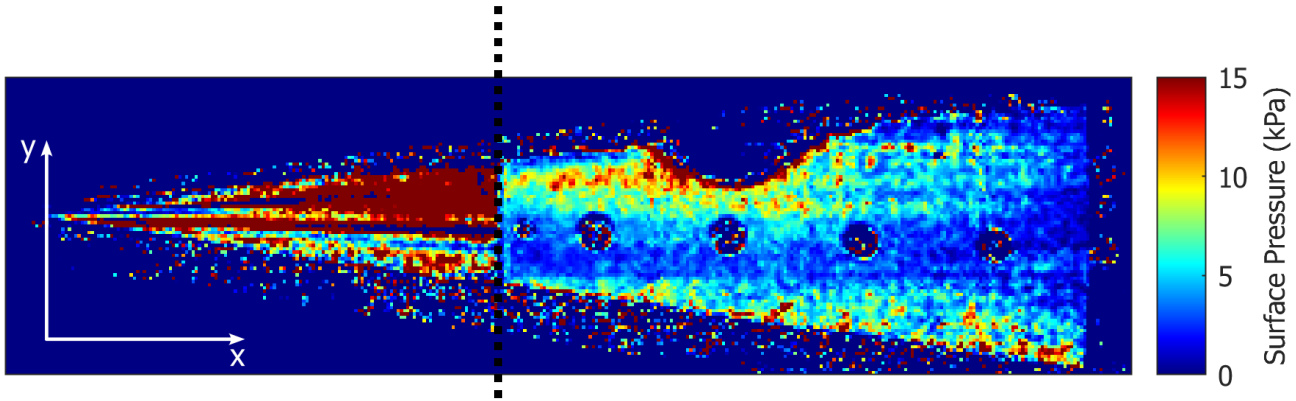
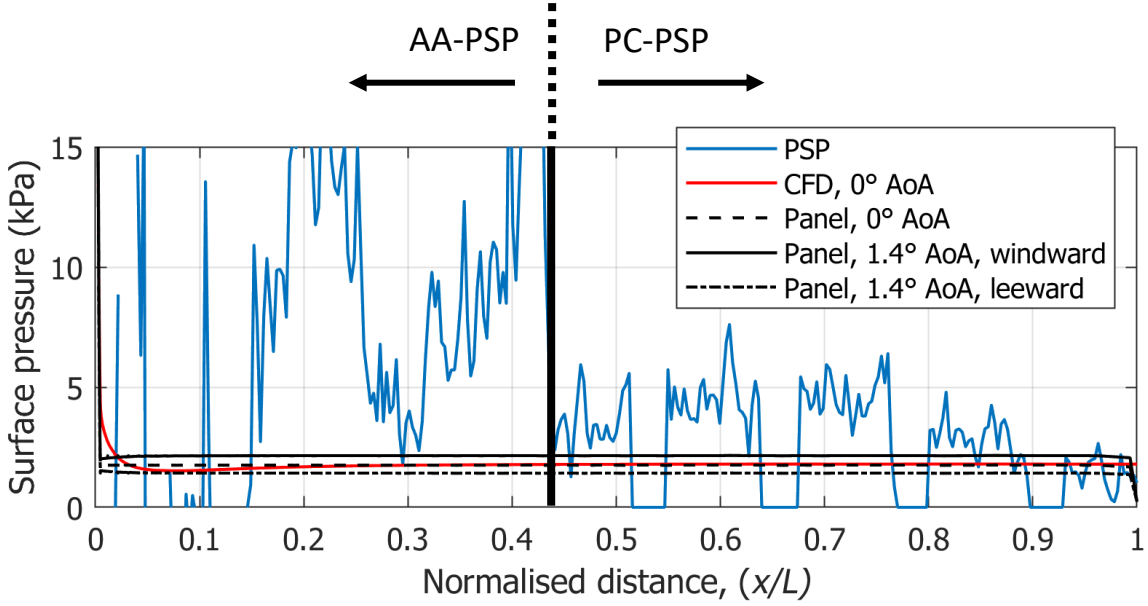
High Density Tunnel (HDT) - Results:

Cone surface pressure during steady test flow period – mid core flow



Comparison of PSP and Numerical pressure distributions along cone mid-line



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Summary:

- Cost-effective Binary PSP method was developed for the Oxford HDT, that was able to resolve intensity maps on a free-flying model.
- Pressure data demonstrated significant non-uniformities.
- Overall the method shows promise as a valid measuring technique.

Further Work:

- Re-analyse post processing technique
- Analyse further Tunnel Runs – possibly static tests
- Investigate effect of desaturating the cameras

References:

- [1]: L. Devices, Pt-120-te product datasheet (2019). URL https://download.luminus.com/datasheets/ Luminus_PT-120_Datasheet.pdf
- [2]: A. Bioquest, Spectrum [fluorescein] (2021). URL https://www.aatbio.com/fluorescence-excitation-emission-spectrum-graph-viewer/Fluorescein
- [3]: M. K. Quinn, L. Yang, K. Kontis, Pressure-sensitive paint: Effect of substrate, Sensors 11 (12) (2011) 11649–11663. doi:10.3390/s111211649.

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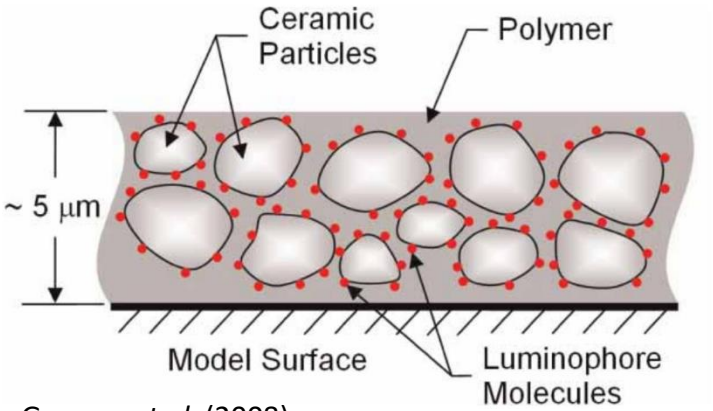
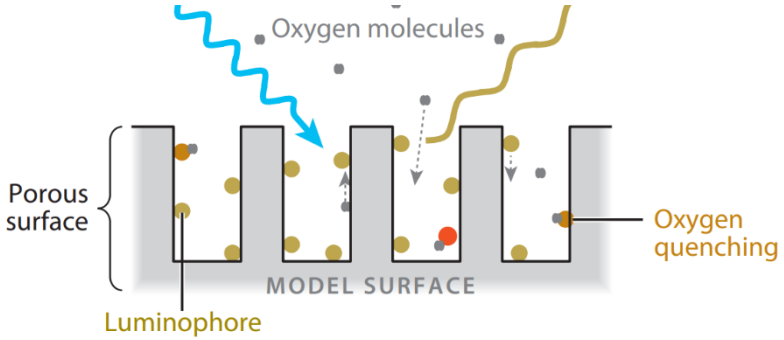
Questions?

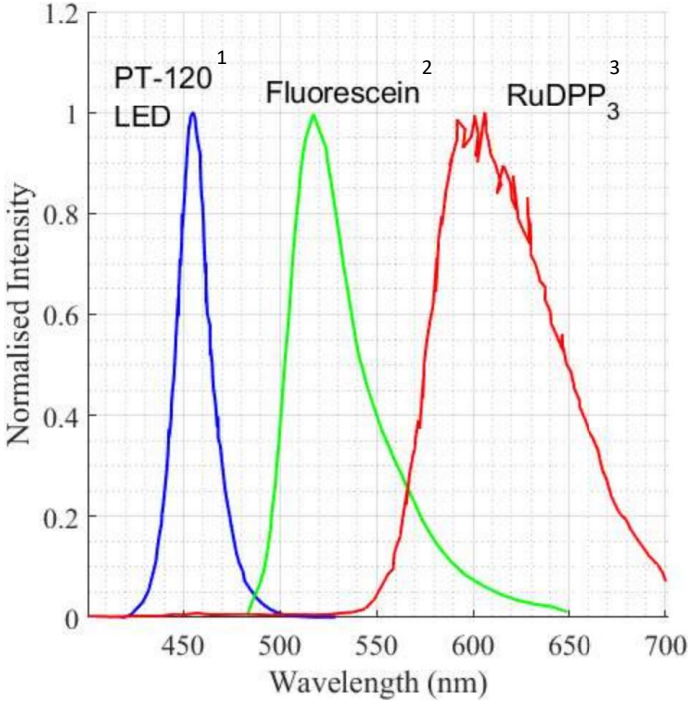
PSP Theory:



Gregory *et al.* (2008)
doi:10.1243/09544100jaero243



Gregory *et al.* (2014)
doi:10.1146/annurev-fluid-010313-141304



Data from: [1], [2] and [3]

Stern-Volmer:

$$\frac{I_{\mathrm{ref}}}{I} = \mathrm{A}(T) + \mathrm{B}(T)\frac{p}{p_{\mathrm{ref}}}$$

Intensity ratio:

$$\frac{\overline{I_{ref}}}{\bar{I}} = \frac{\frac{I_{p,\mathrm{ref}}}{I_p}}{\frac{I_{r,\mathrm{ref}}}{I_r}}$$

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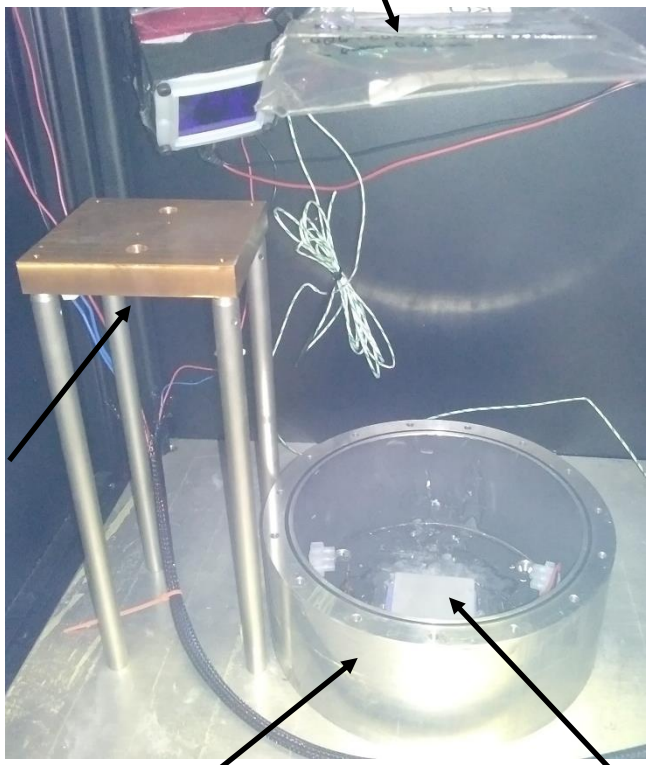
Benchtop Testing:

Vacuum pump
(Edwards E2M1.5)

Hand pump
(Additel 914)

LED
(Luminus PT-120-B)

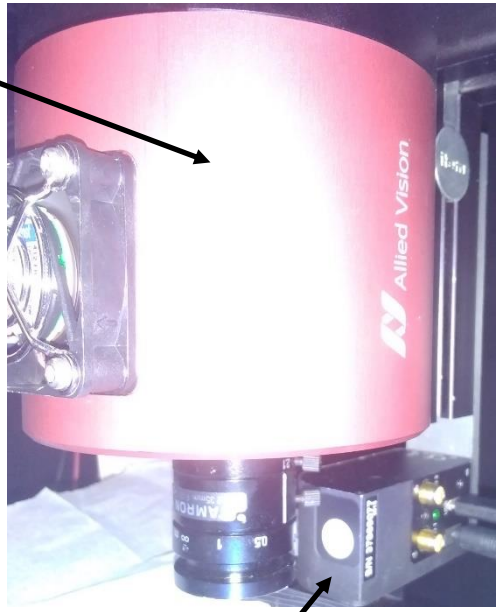
Filter



Pressure vessel

Peltier Cooler
(Adaptive ET-127)

CCD Camera
(Bigeye G-283B Mono)



Filter Flipper
(Thorlabs MFF102)

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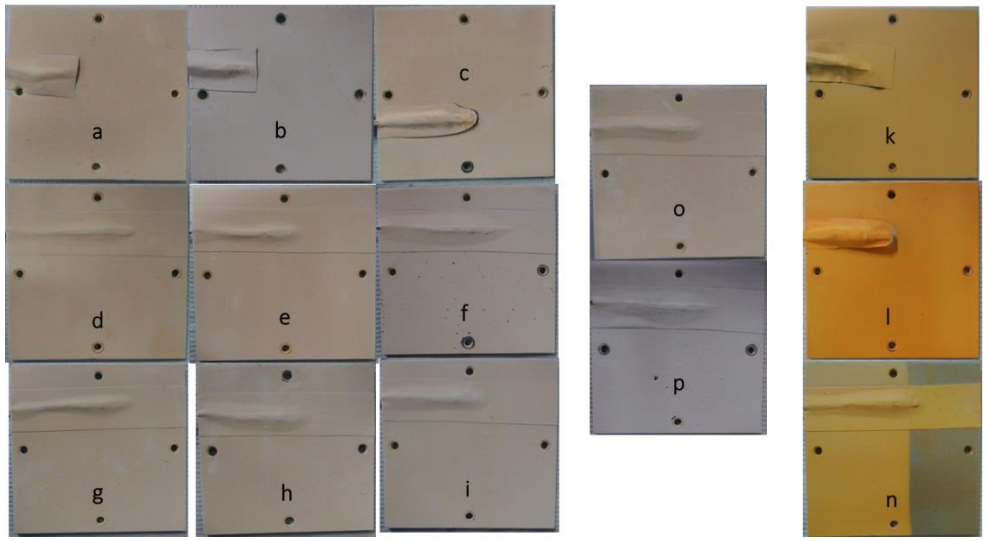
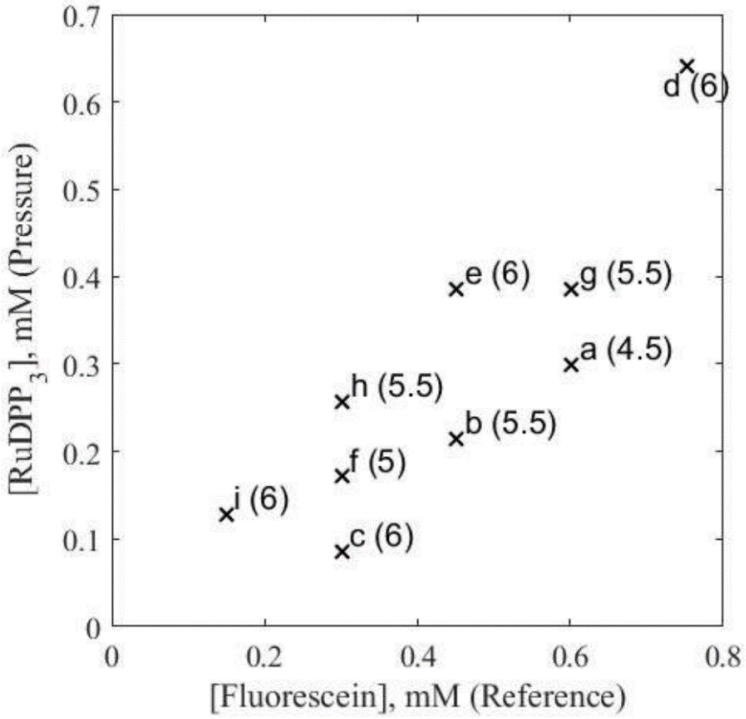
Benchtop Testing:





Single-component

PC-PSP

AA-PSP

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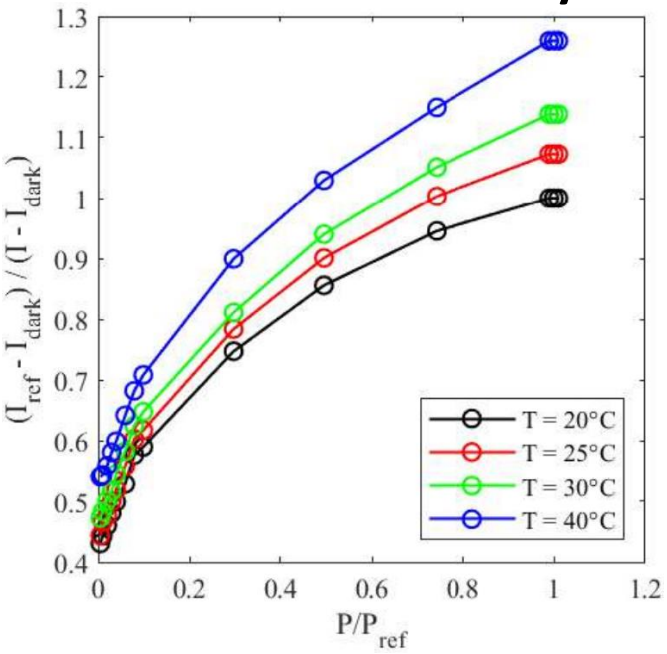
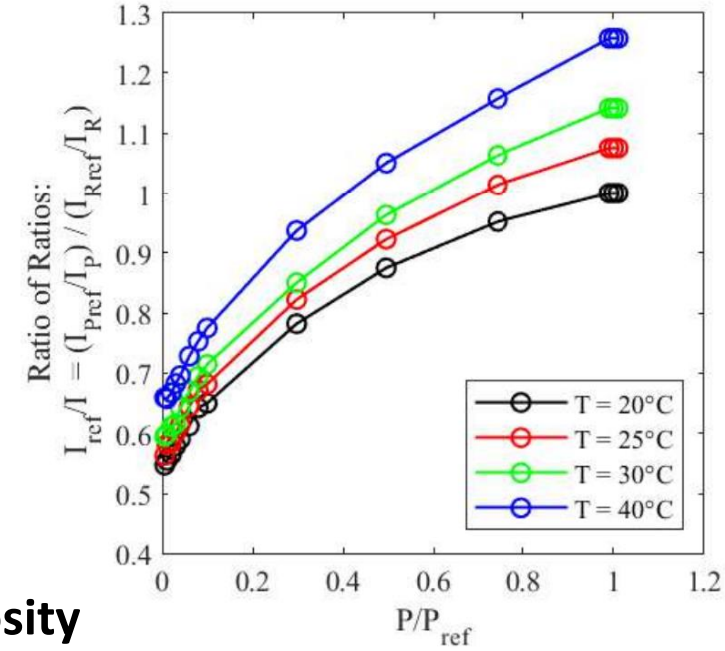
Benchtop Testing - Results

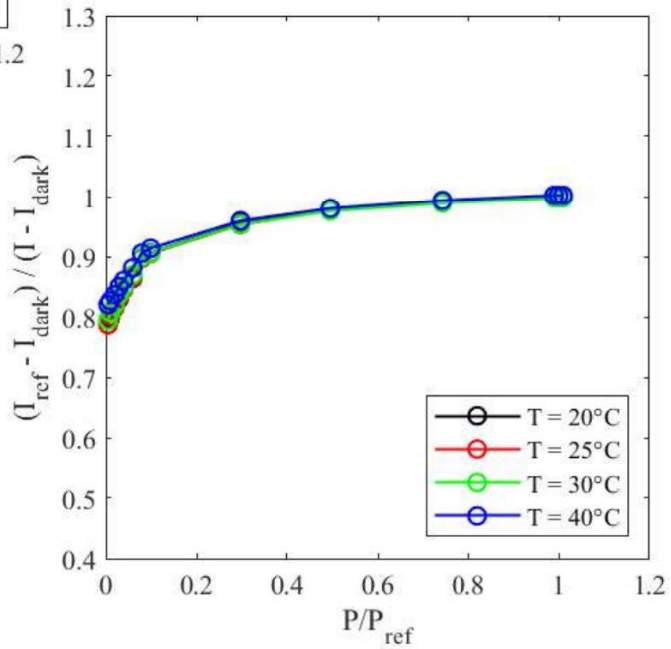
RuDPP3 Luminosity



Ratio-of-ratios



Fluorescein Luminosity



Sample calibration results for coupon *b*. P_{ref} is 100 kPa.

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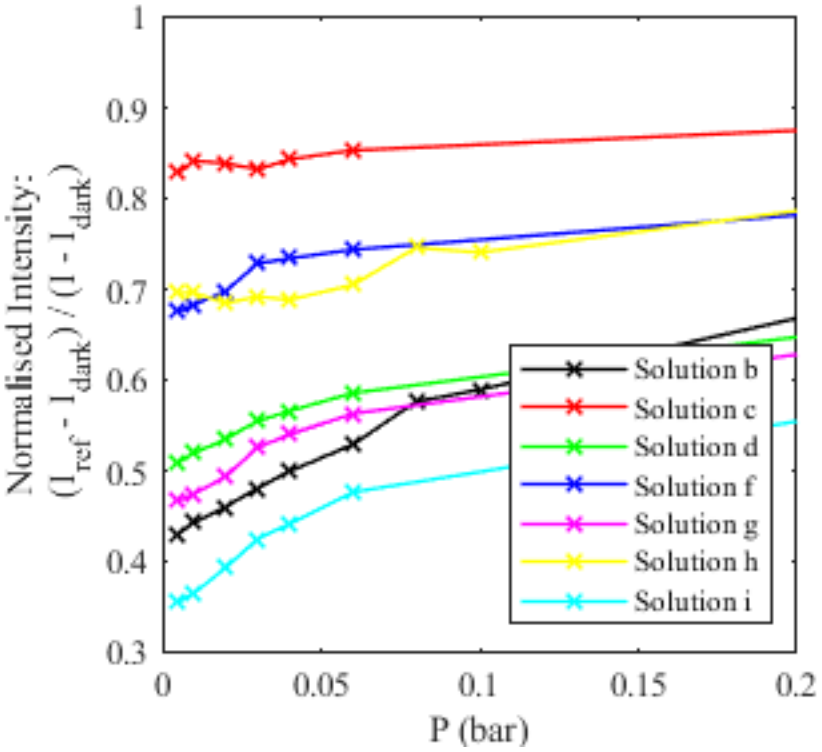
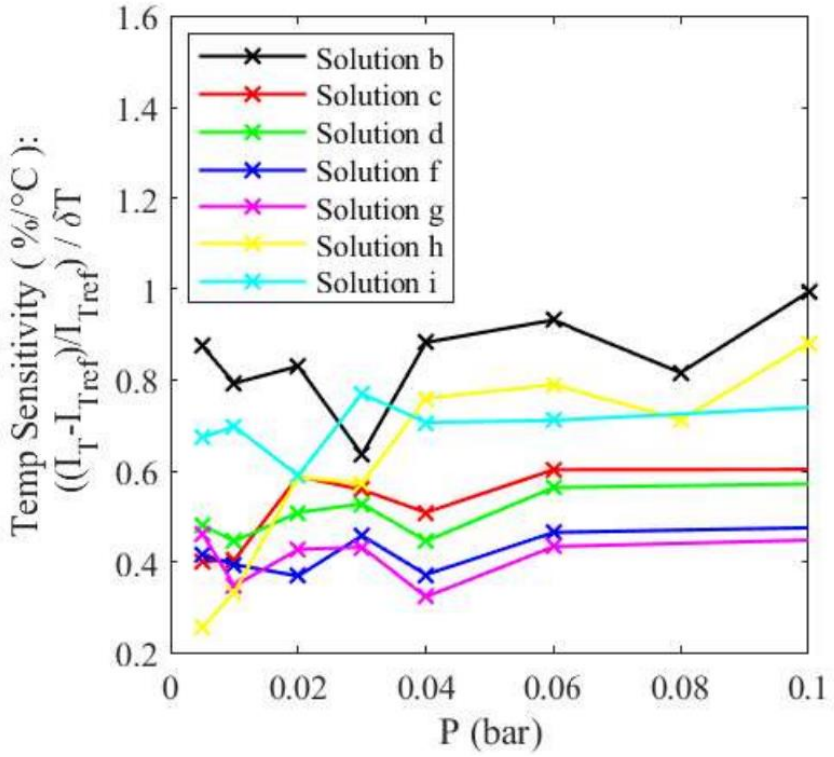
Benchtop Testing - Results



$$\frac{I_{ref} - I_{dark}}{I - I_{dark}}$$ Pressure signal sensitivity



$$\frac{\frac{I_T - I_{T,ref}}{I_{T,ref}}}{\Delta T}$$ Temperature sensitivity (between 20 and 30 ° C)

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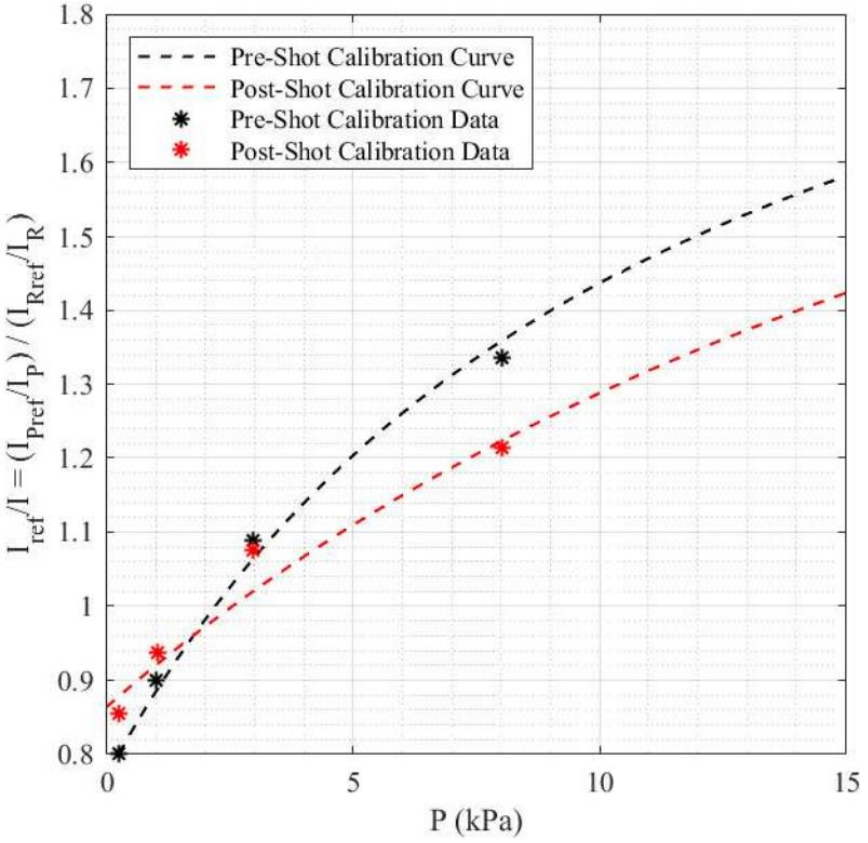
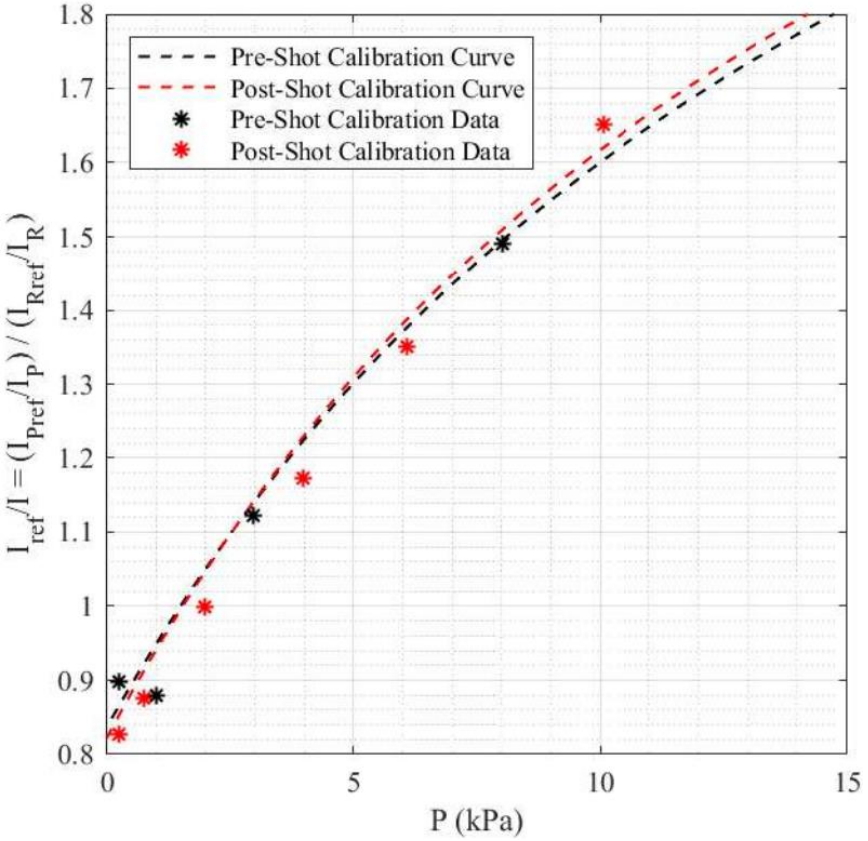
High Density Tunnel (HDT) - Processing:



PC-PSP



AA-PSP

$$\frac{\overline{I_{ref}}}{\bar{I}} = \frac{\frac{I_{p,\mathrm{ref}}}{I_p}}{\frac{I_{r,\mathrm{ref}}}{I_r}} = \frac{K_1 - K_2 p}{K_3 - K_4 p}$$

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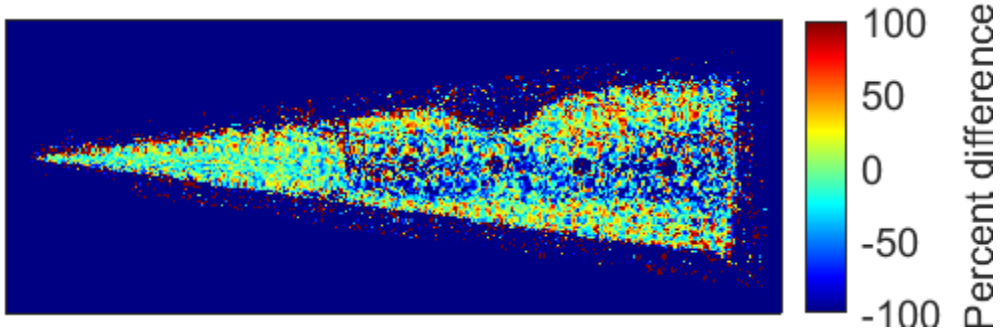
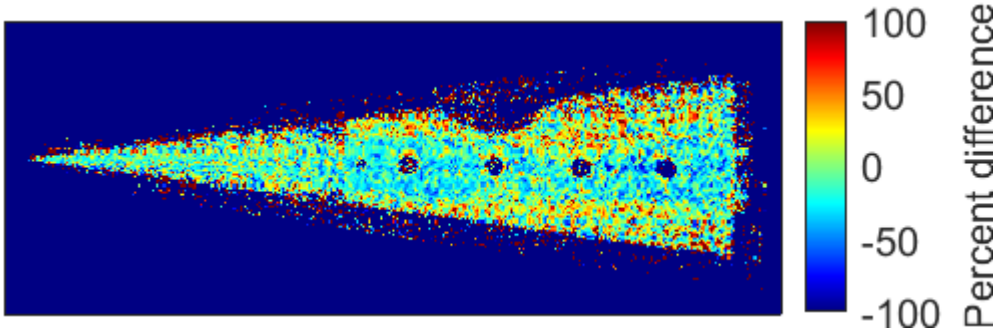
High Density Tunnel (HDT) - Results:

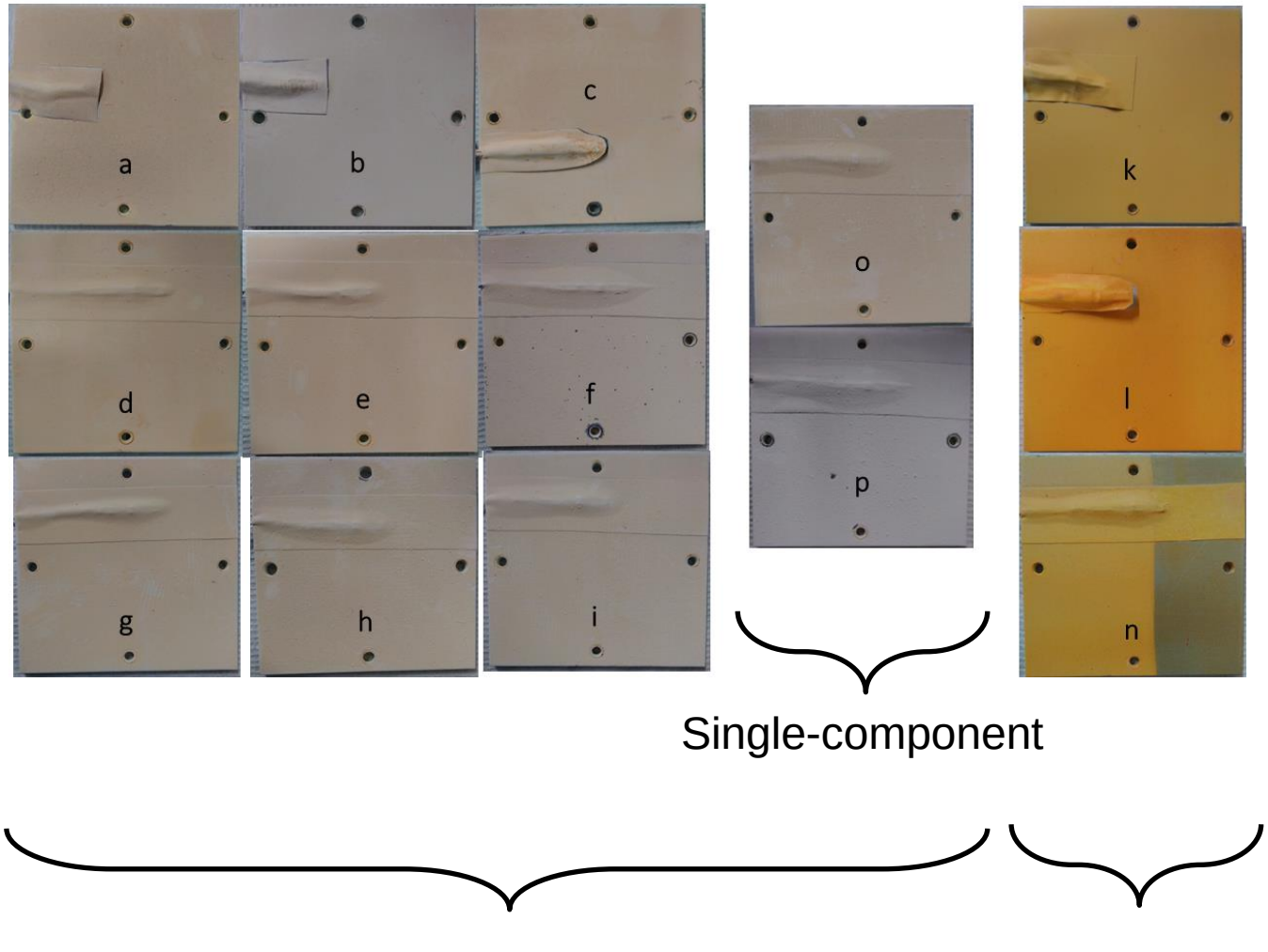


Pixel-by-pixel calibration



“Single-Curve” calibration

Benchtop Testing:



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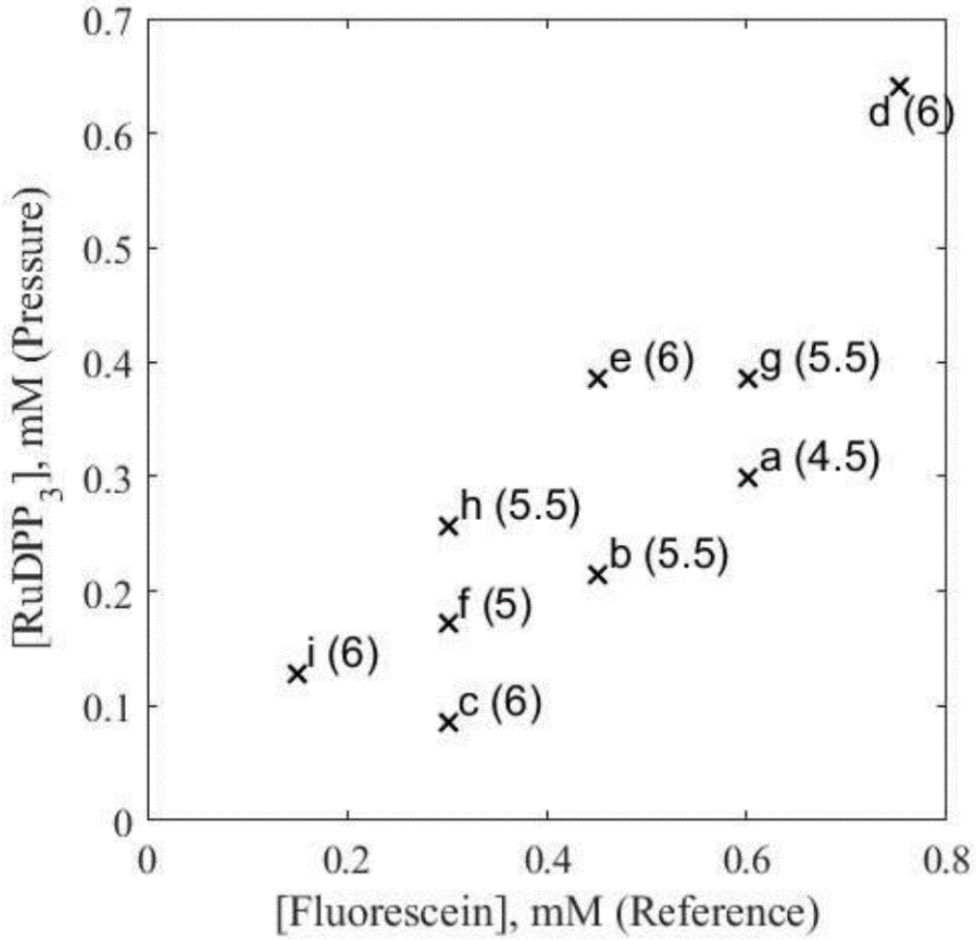
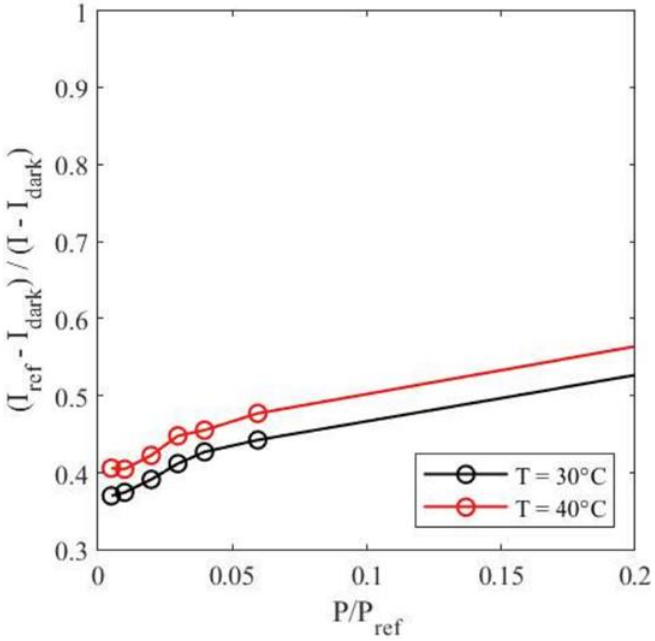
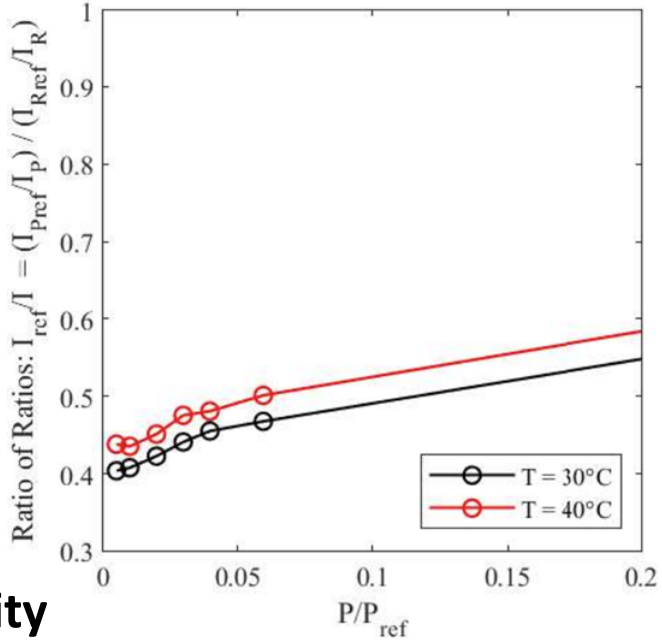


Benchtop Testing - Results

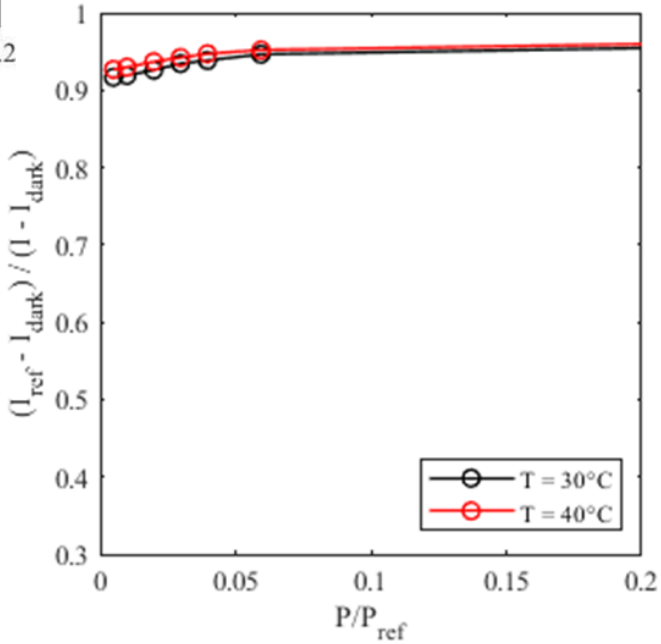
RuDPP3 Luminosity



Ratio-of-ratios



Fluorescein Luminosity



Sample calibration results for coupon *i*. Green dichroic filter held at 45° for reference signal.

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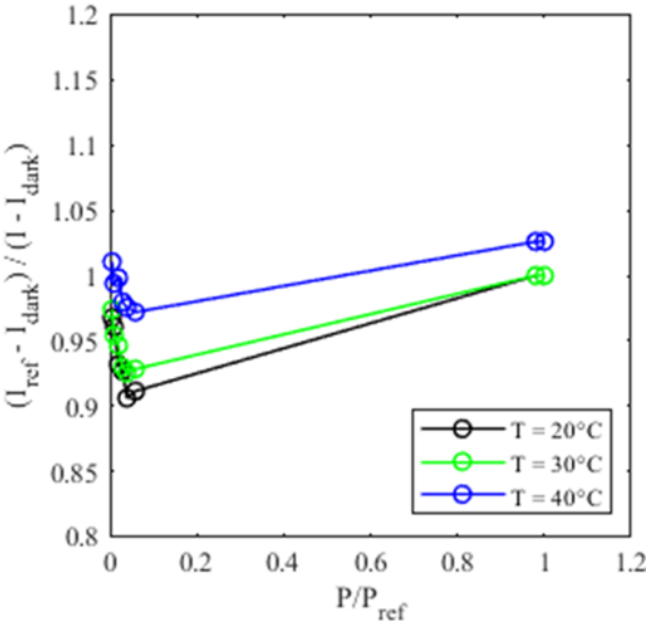
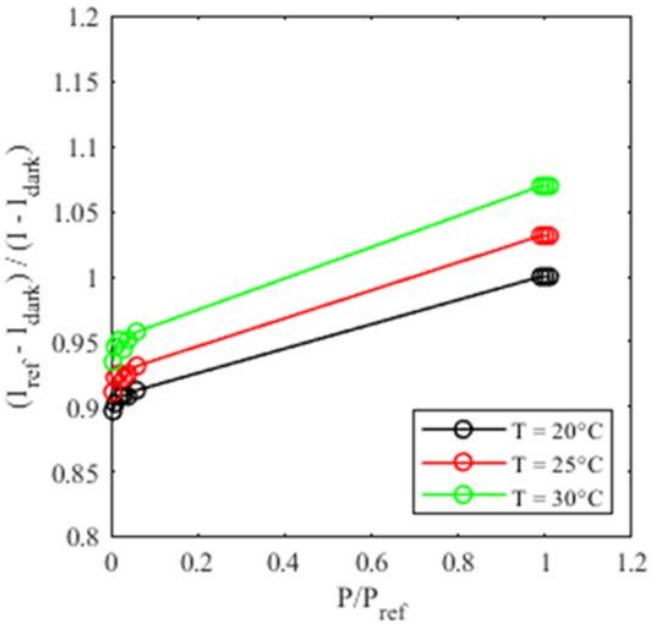
Benchtop Testing - Results

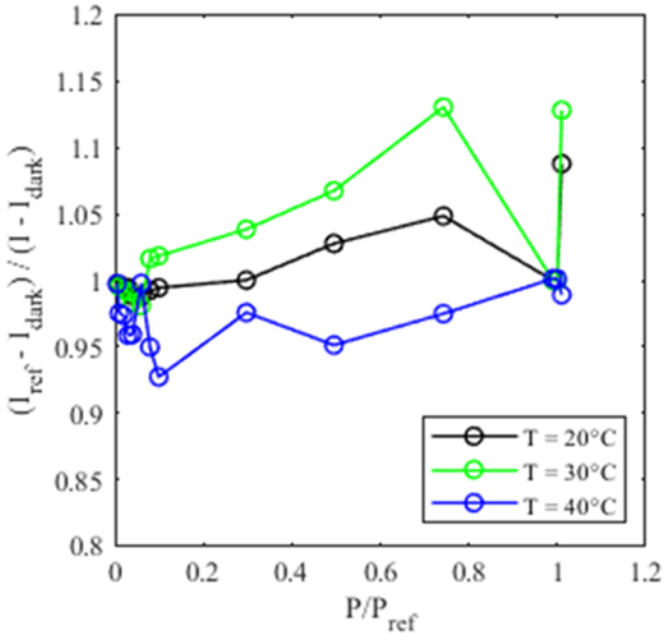
Coupon *k*



Coupon *n*



Coupon *l*



Sample calibration results for AA-PSP coupons – pressure signals (RuDPP3).

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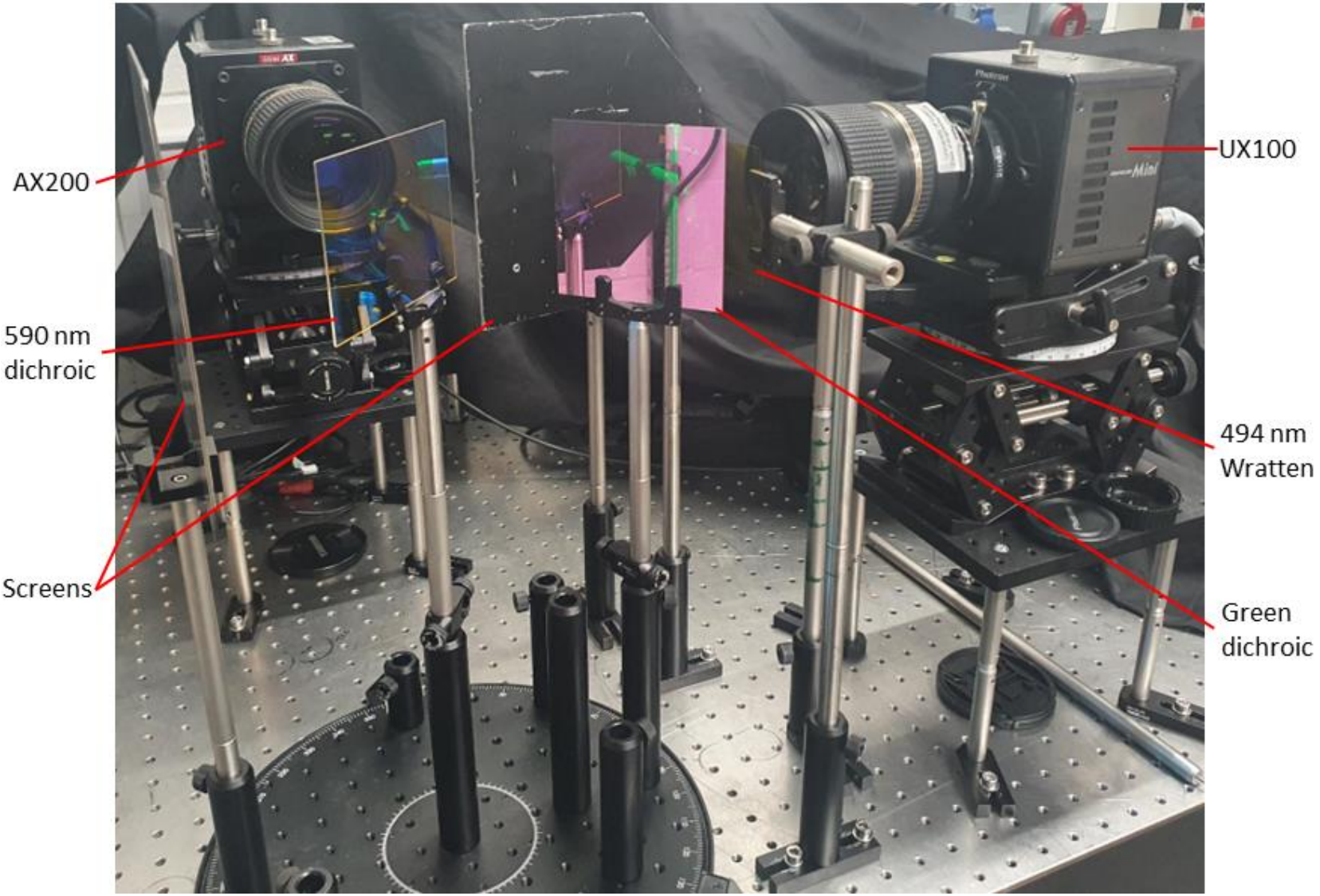
HDT Experimental Setup



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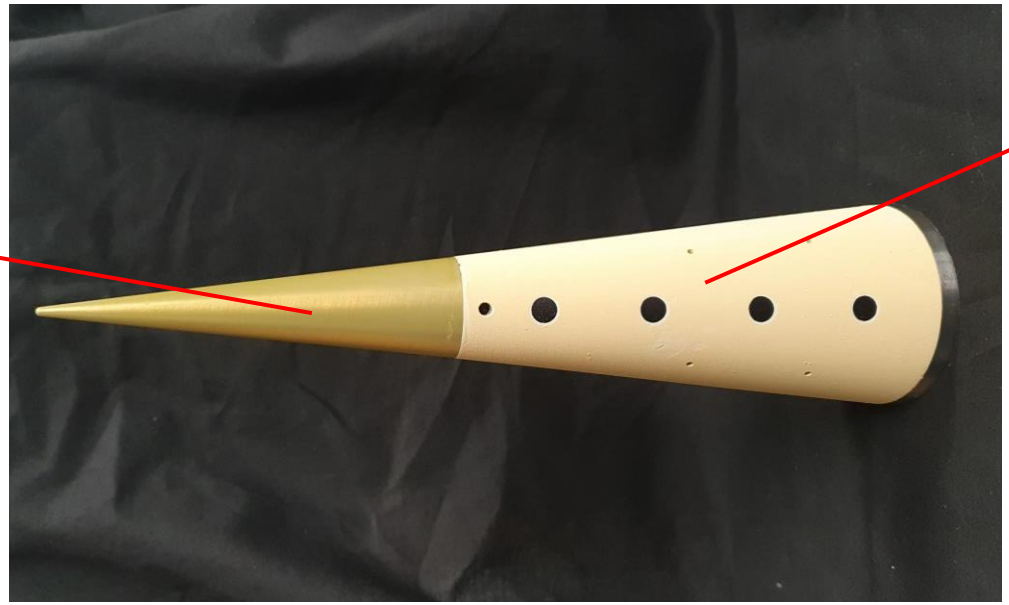
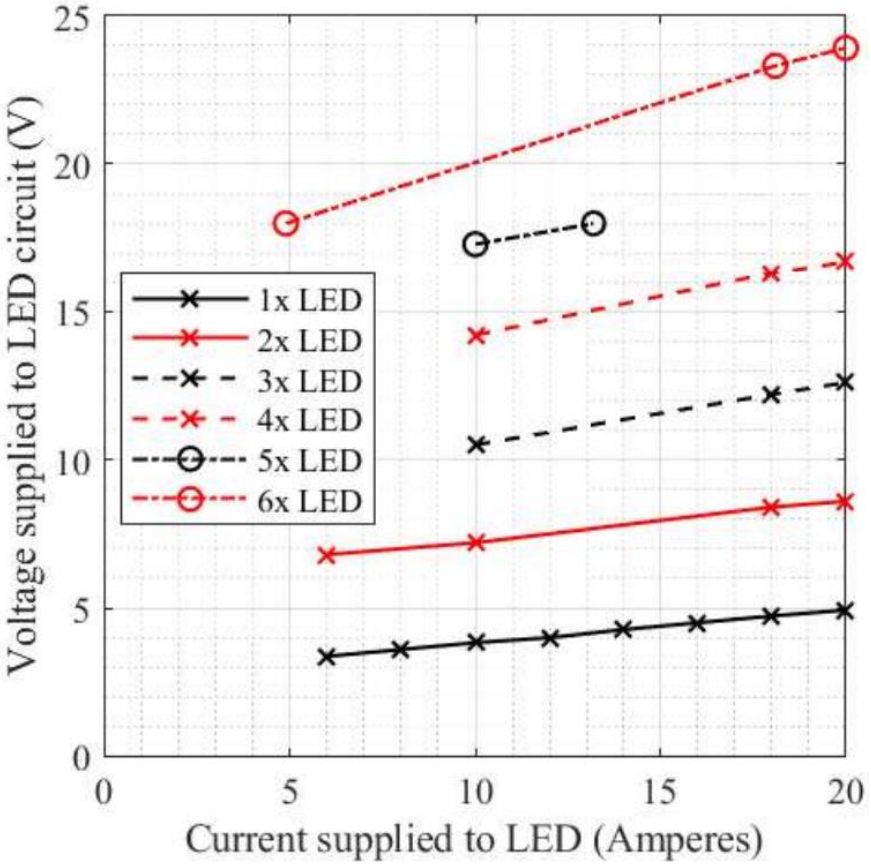
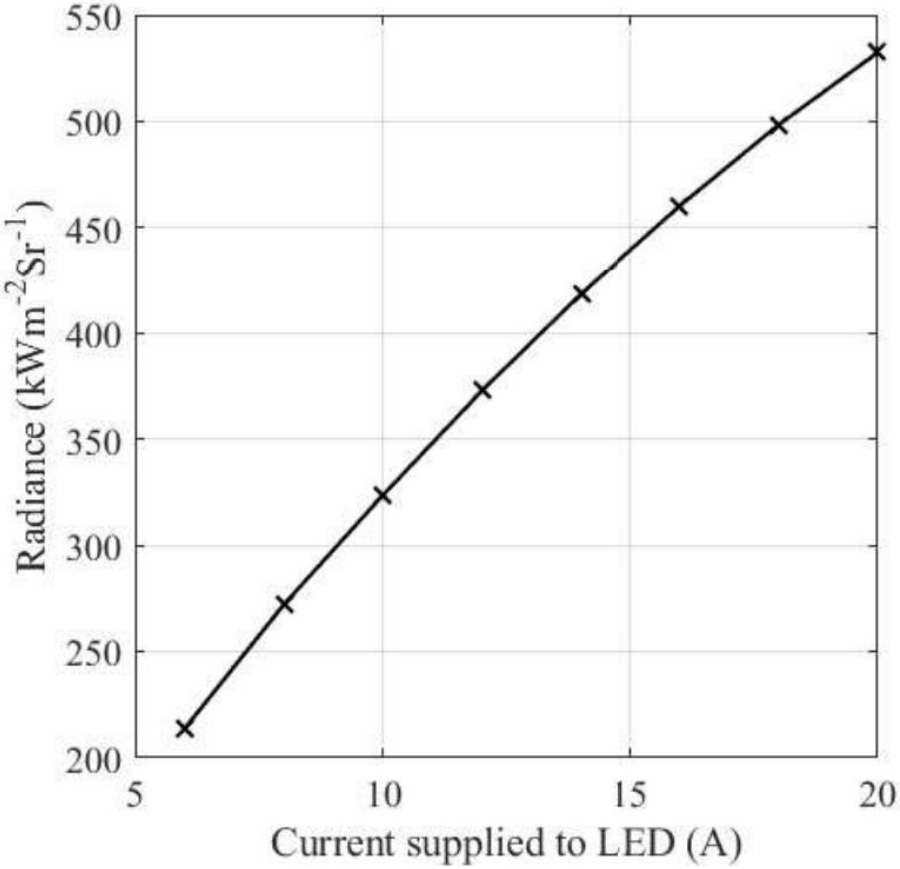
HDT Experimental Setup

Solution:		(1)			(2)				Luminophore Concentration			
No:	Type:	$RuDPP_3$ (X mg)	Fluorescein (Y mg)	DCM (ml)	RTV-118 (mg)	TiO_2 (g)	Toluene (ml)		Ru:F (1:x)	[Fluores] [mM]	[$RuDpp_3$] [mM]	[Ru + F] [mM]
j (cone)	PC-PSP	37.41	15.95	24	1200	6.8	56		1.5	0.6	0.4	1.0
m (tip)	AA-PSP	7.02	3.99	30	N/A	N/A	N/A		1.3	0.4	0.2	0.7



HDT Experimental Setup





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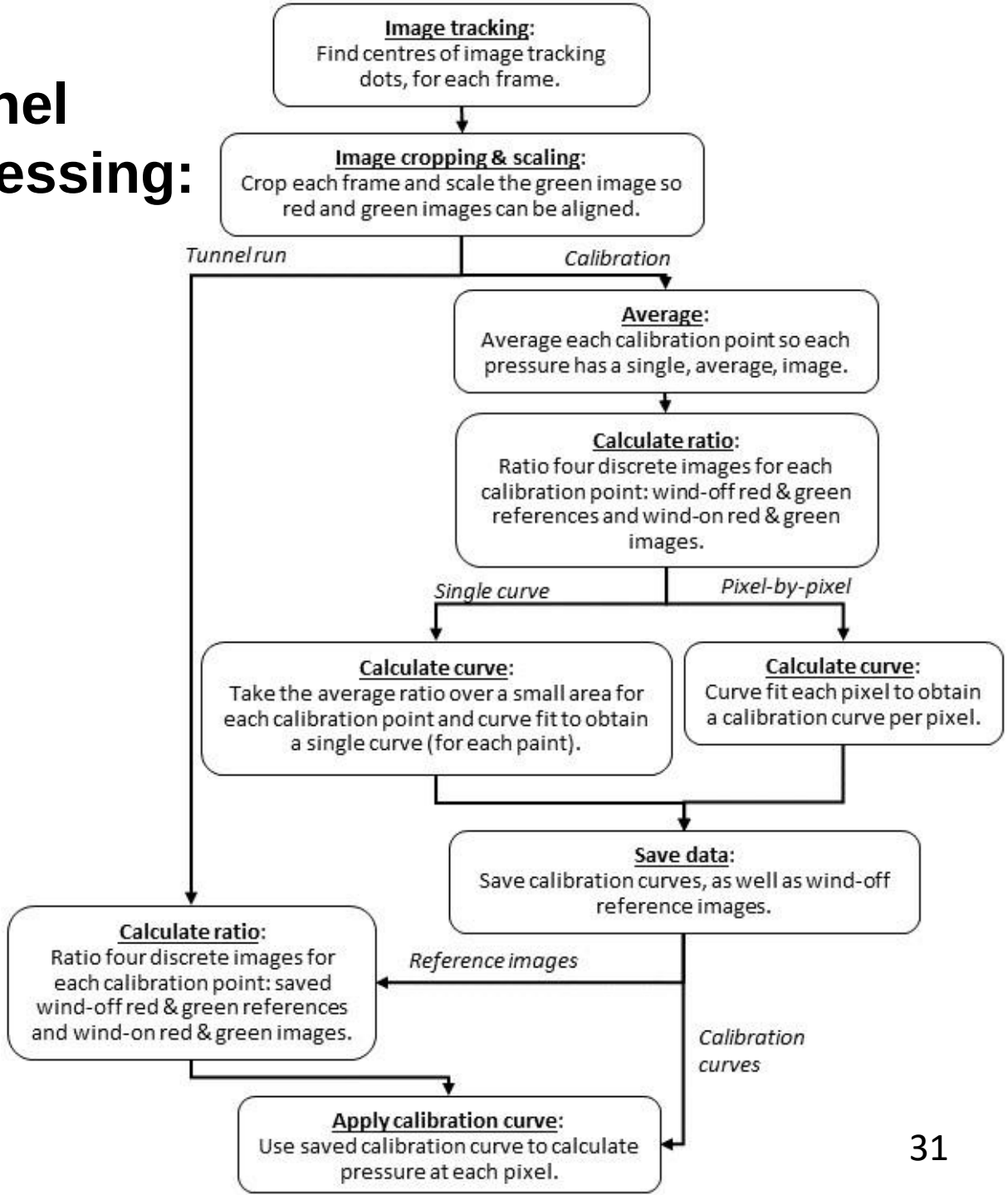
High Density Tunnel (HDT) - Post-processing:



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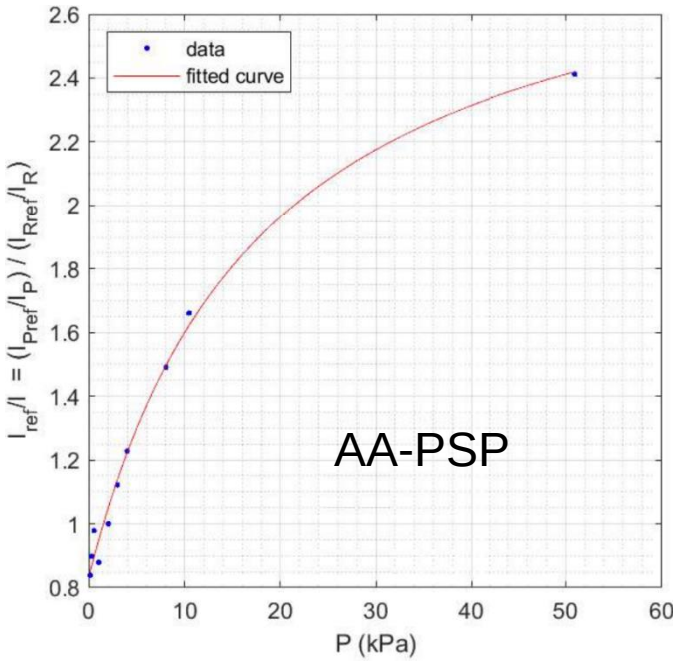
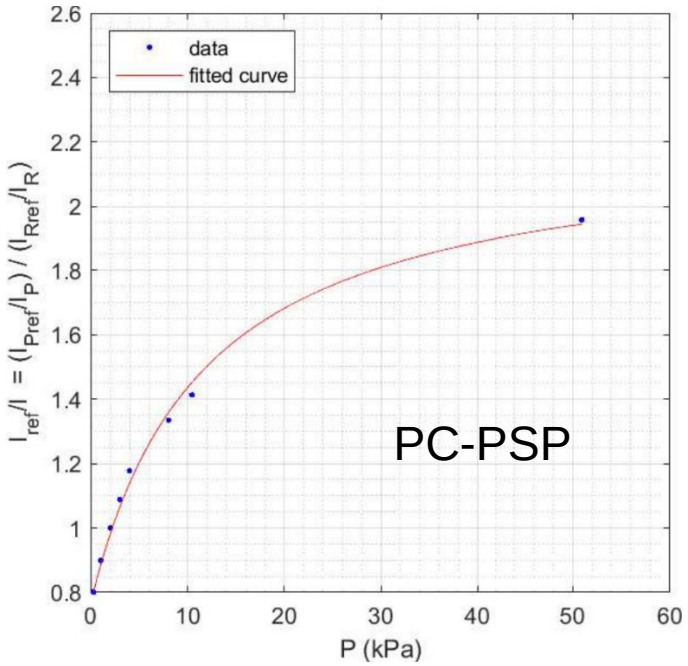
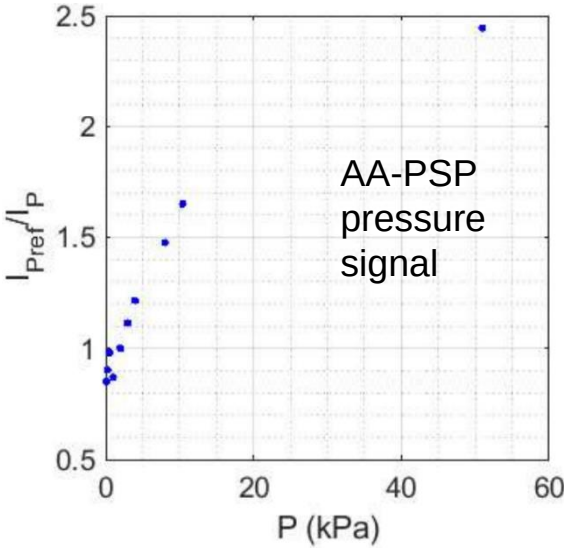
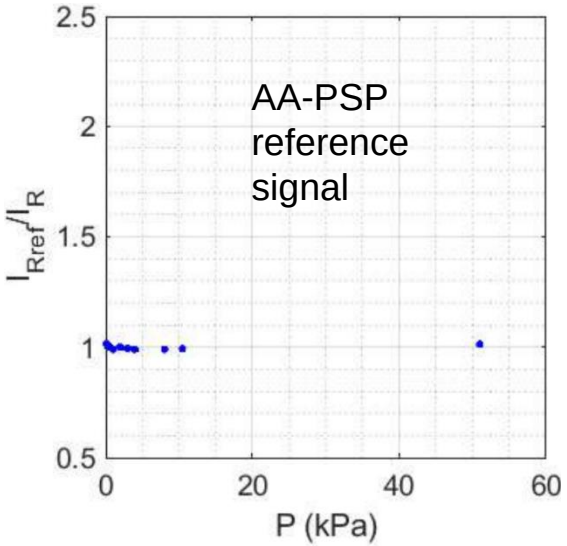
In-situ Calibration:









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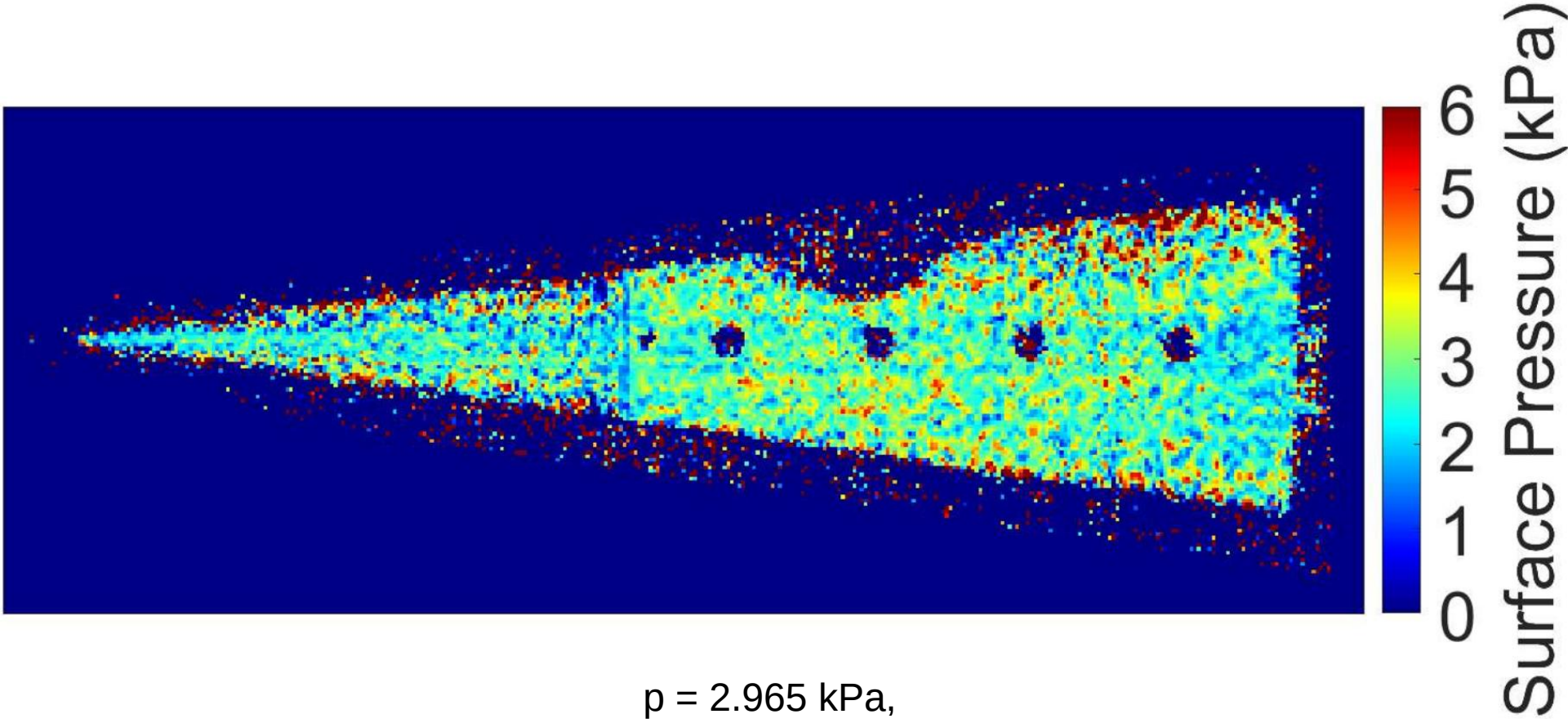
In-situ Calibration



p = 2.965 kPa,

Reference: p = 2 kPa

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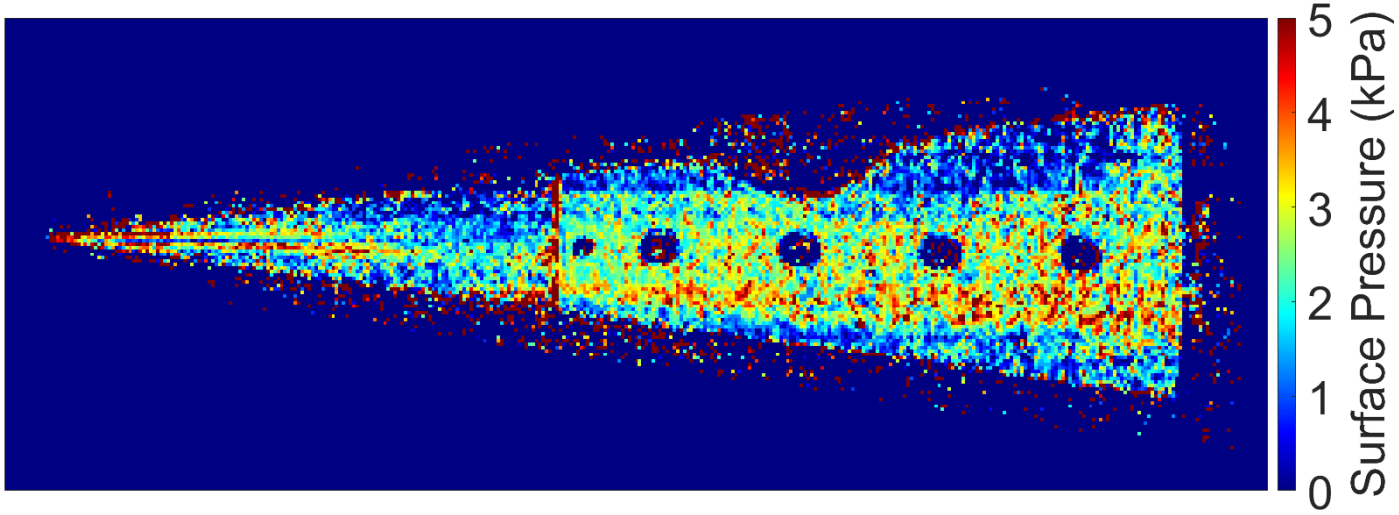
Free-flying Tunnel Run

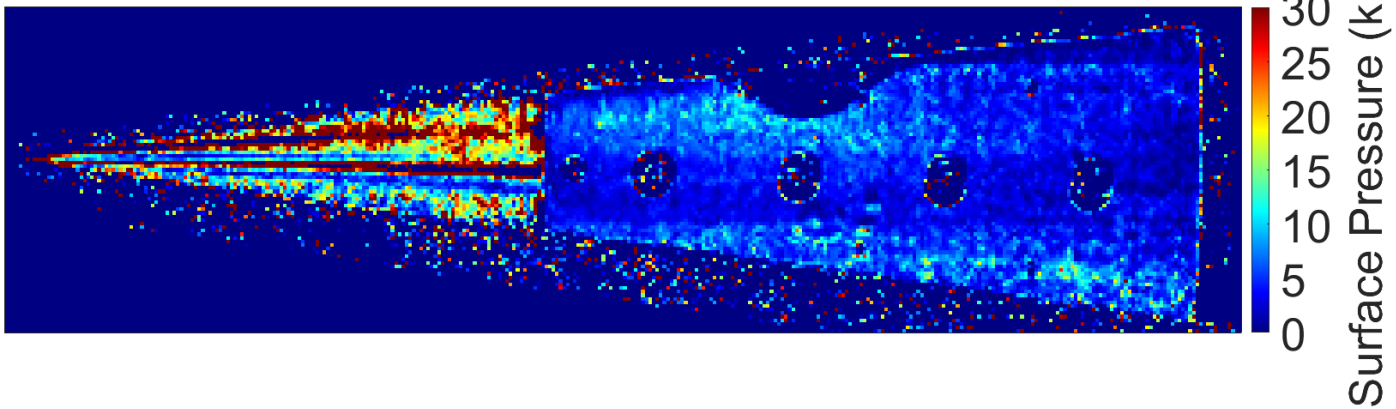
t = 3 ms,

Reference: p = 2 kPa



t = 200 ms,

Reference: p = 2 kPa



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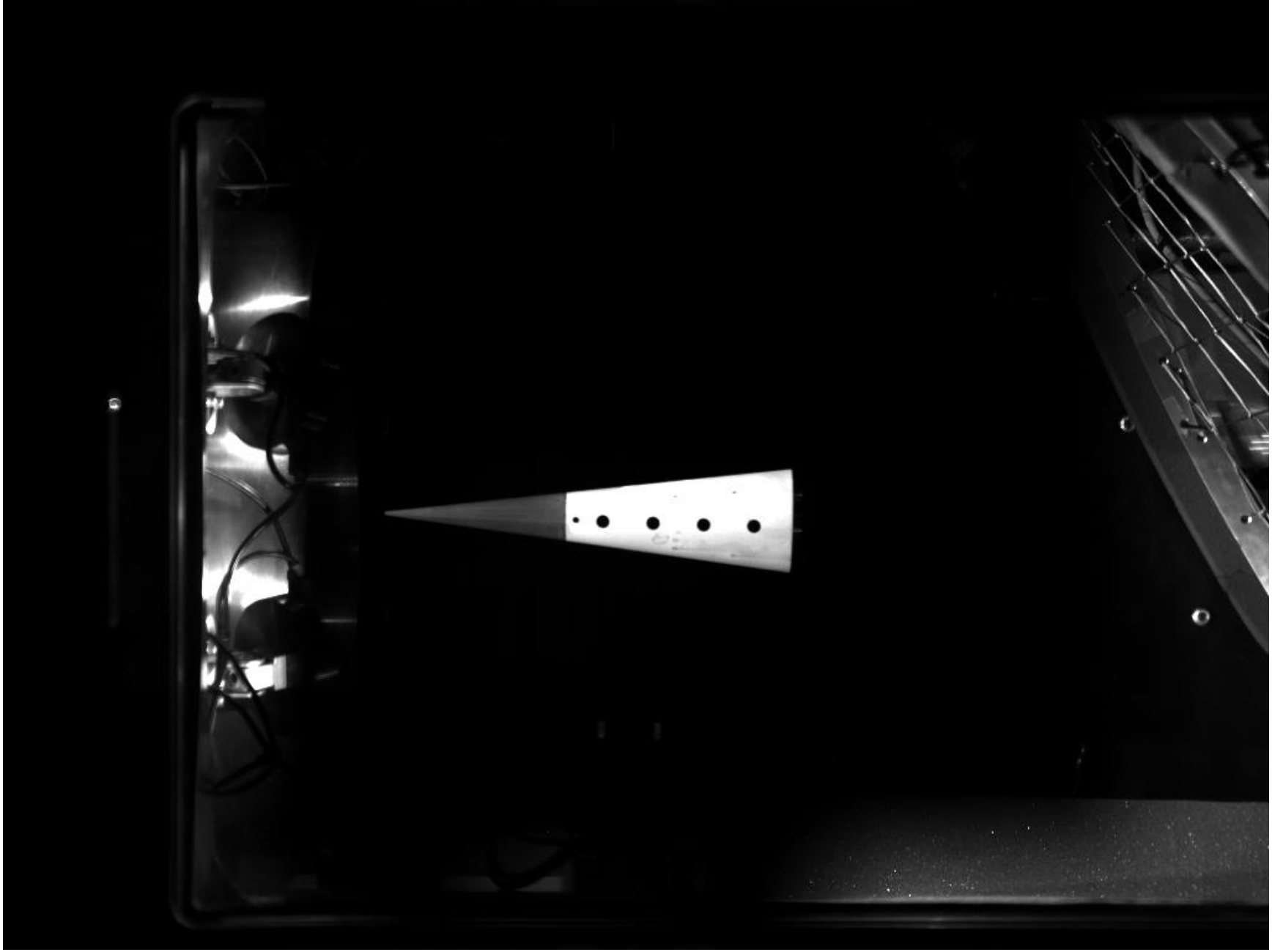
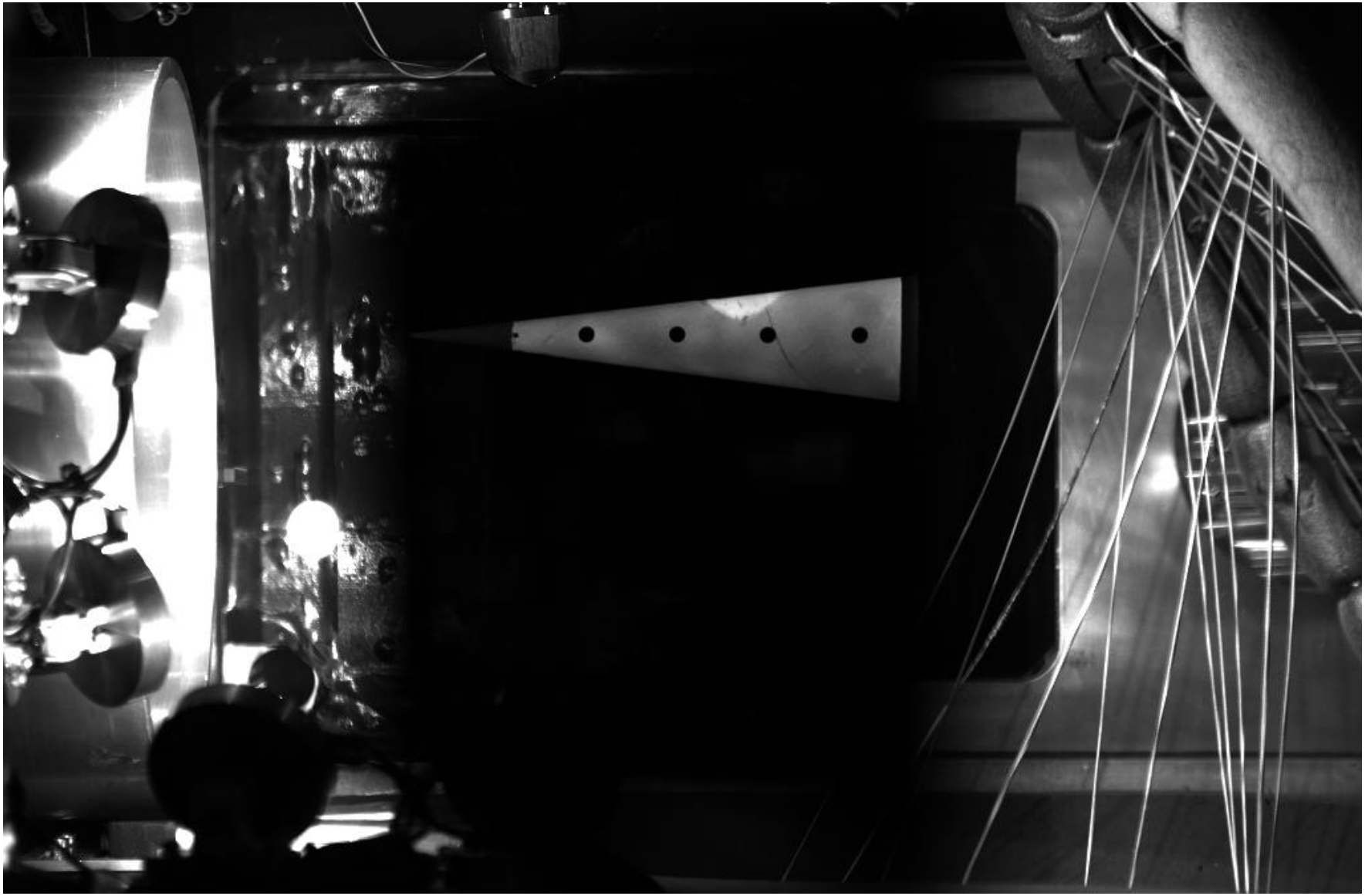
PSP Theory (Brief)

$$\frac{I_{\mathrm{ref}}}{I} = \frac{\frac{I_{p,\mathrm{ref}}}{I_p}}{\frac{I_{r,\mathrm{ref}}}{I_r}} = \frac{\mathrm{A}_p(T)+\mathrm{B}_p(T)\frac{p}{p_{\mathrm{ref}}}}{\mathrm{A}_r(T)+\mathrm{B}_r(T)\frac{p}{p_{\mathrm{ref}}}} = \frac{\mathrm{A}_p(T)+\mathrm{B}_p(T)\frac{p}{p_{\mathrm{ref}}}}{\mathrm{A}_r(T)} = \mathrm{A}'(T) + \mathrm{B}'(T)\frac{p}{p_{\mathrm{ref}}}$$





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