Invited: Error Estimation for Unsteady Pressure Sensitive Paint Measurements



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AMT-04/SD-04/GT-04: Invited: NASA Ames Unsteady PSP Development for Testing and Evaluation

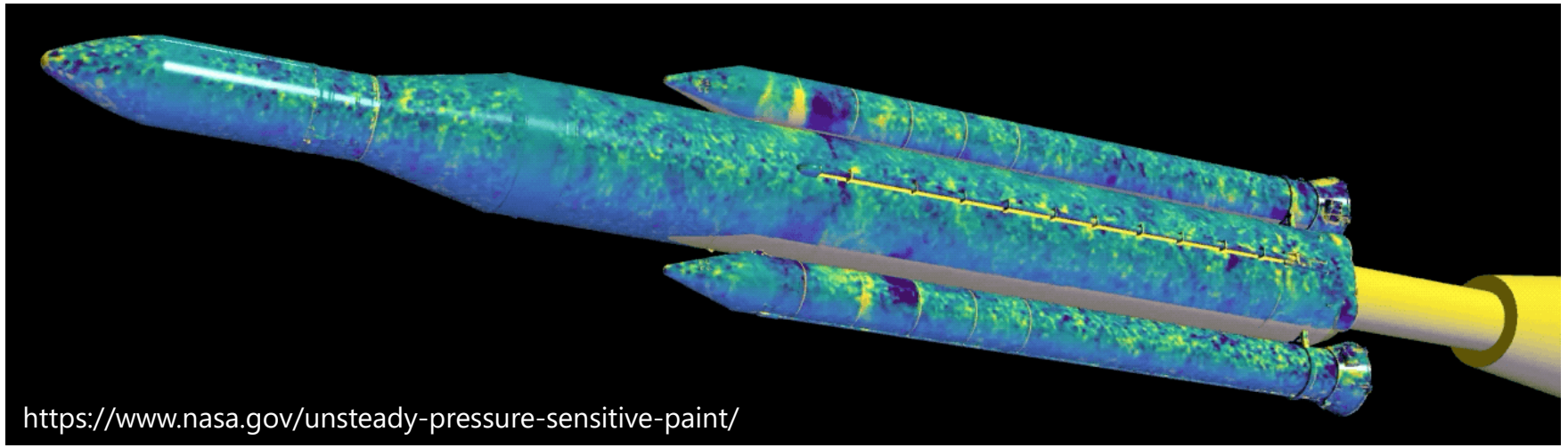
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Motivation

Unsteady Pressure Sensitive Paint (uPSP) produces valuable full model pressure measurements



- Like having a million microphones over your model
- But noise floor is a major consideration (often ~140 dB SPL)
  - Noise floor caused by camera random noise (e.g. SPL you'd see in wind-off)
- A quantitive model for estimating noise floor is desired for test planning and data quality checks
  - Test Planning: "Given my requirements, how bright does my image need to be?"
  - Data Quality: "Is my paint still bright enough to meet requirements?" (photodegradation)

Developing a Noise Model

- Camera Noise (Bias errors and Random errors)
  - Random Noise — *Shot Noise and Read Noise*
  - Fixed Pattern Noise (FPN) — *Static Patterns*
  - Periodic Noise — *Time-Varying Patterns*
- Paint Response
  - New (?) paint model, Pumpdown paint calibration
  - Spatial nonuniformity
- PSP Processing
  - Propagation of errors through the PSP working equations
- Noise Floor Maps

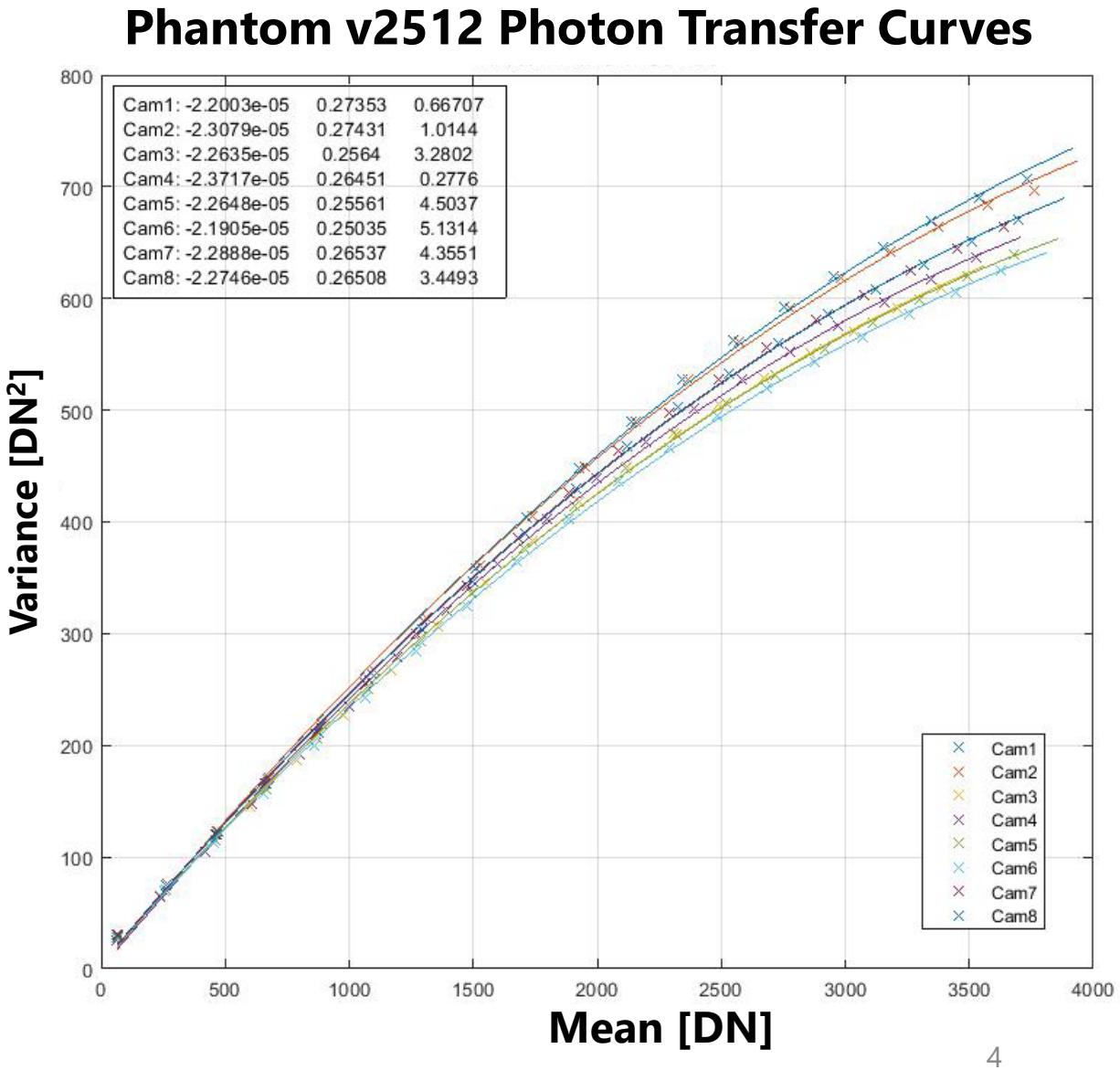
Camera Random Noise

Read noise (offset)

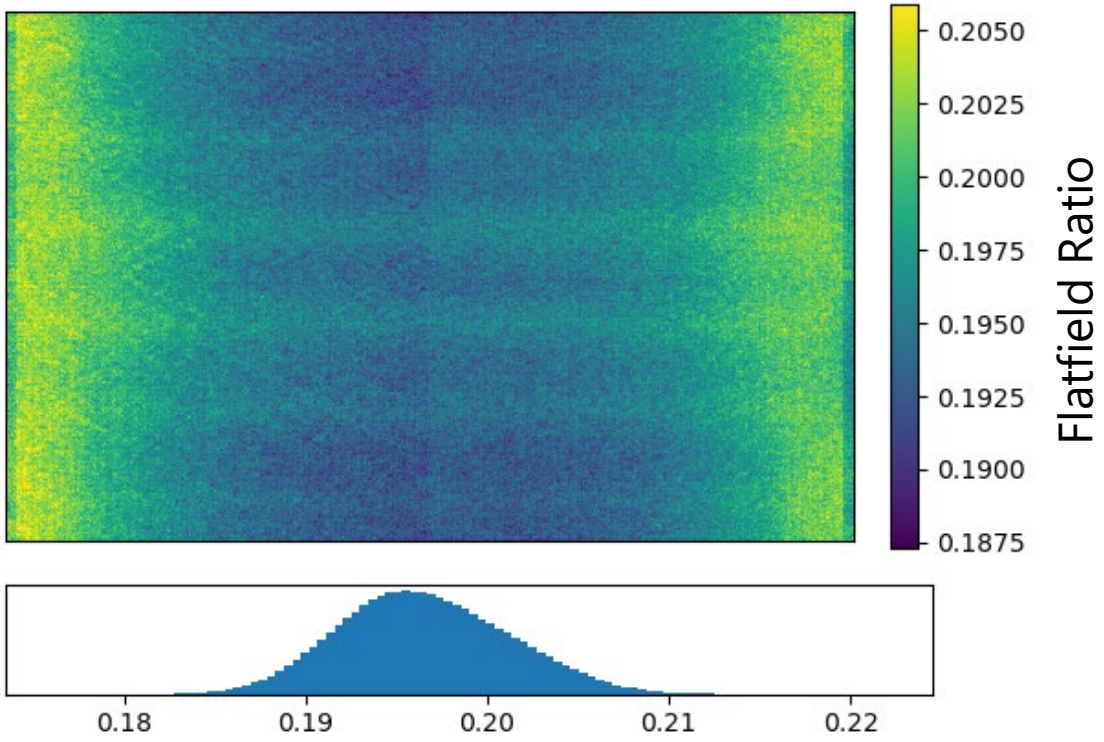
- Due to pixel readout circuitry
- Constant variance (~25 DN^2)

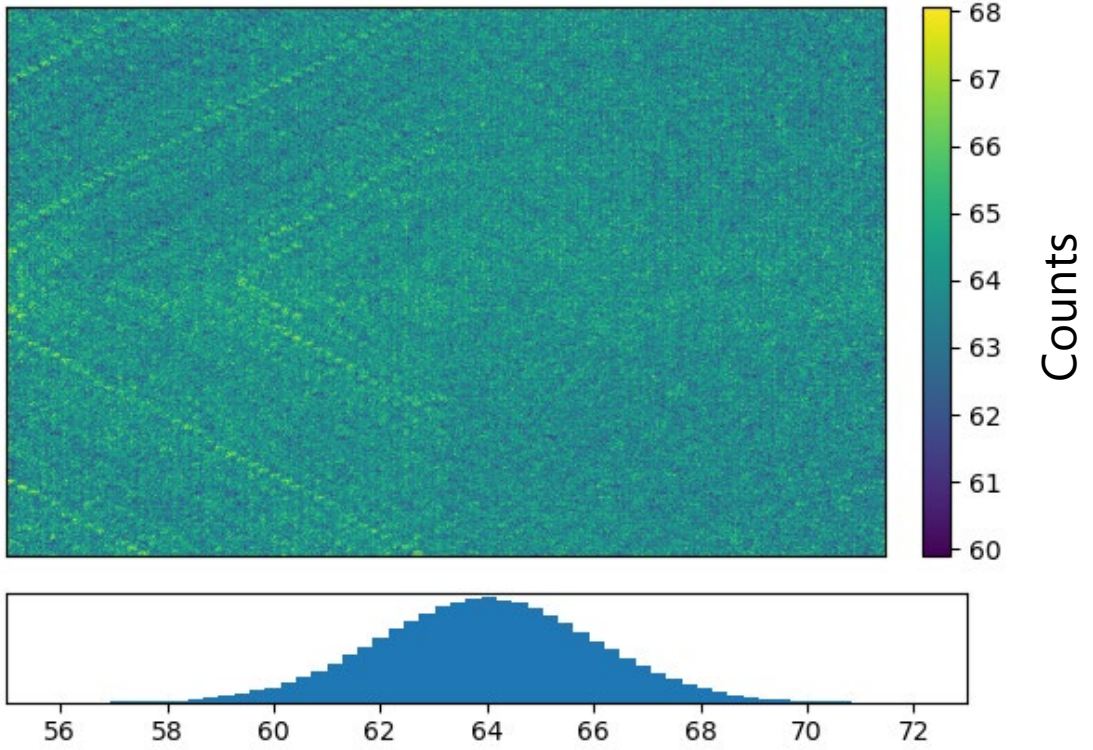
Shot noise (slope)

- Due to discrete nature of photons
- Poisson distributed
  - Variance [e^-] = Mean [e^-]
  - Variance [DN] = Pixel Gain * Mean [DN]
- Pixel Gain ~ 0.25 DN per photoelectron



Other Camera Noise

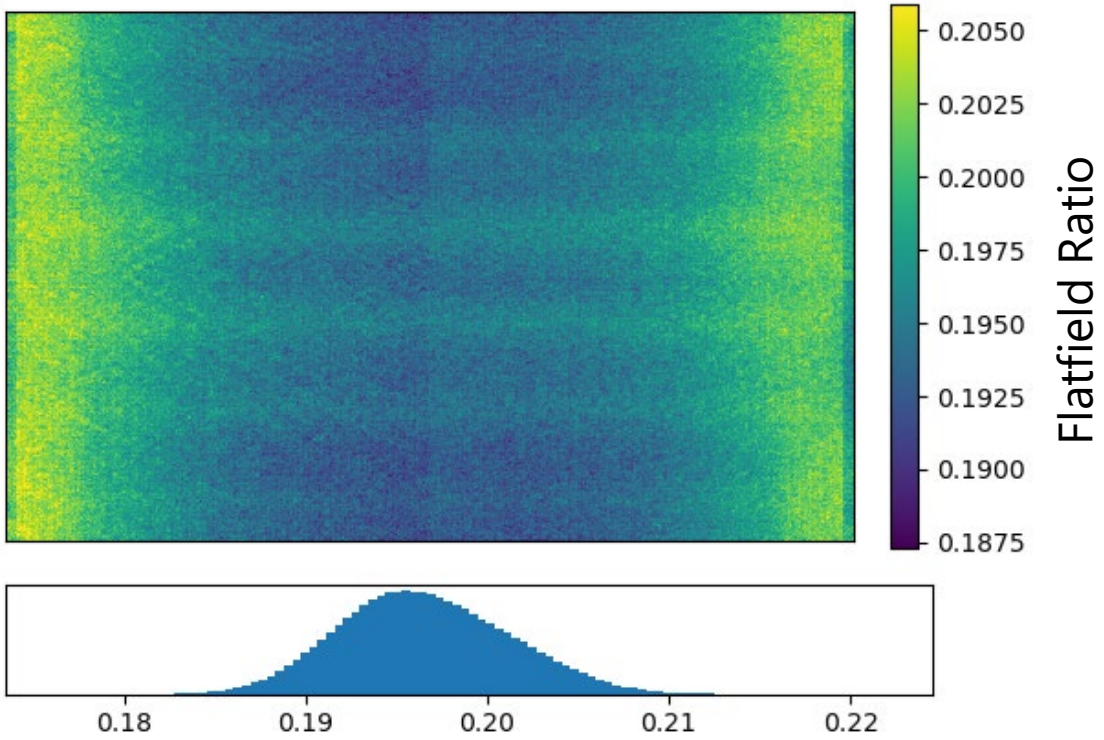


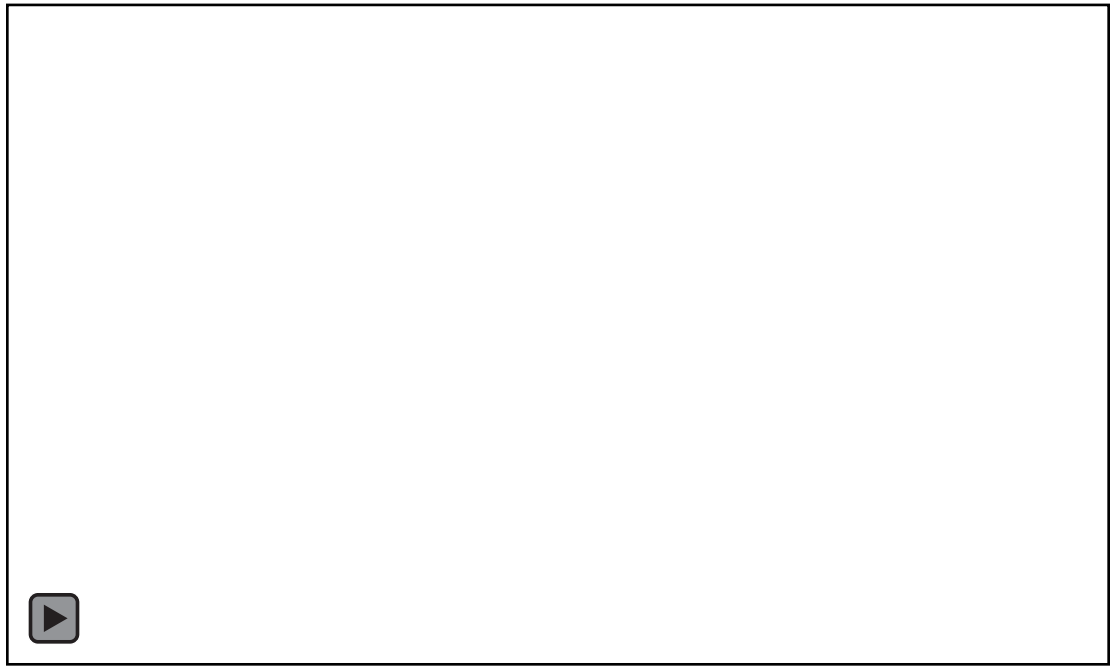


Photoresponse Non-Uniformity (PRNU)
- Per pixel differences in gain
- Characterized using flatfield images
- Can be discernable in PSP results

Periodic Noise
- Time varying patterns in video
- Low amplitude (a few counts)
- Produces spurious peaks in PSD

Other Camera Noise





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Paint Response

Current paint cal method (laboratory, single calibration)

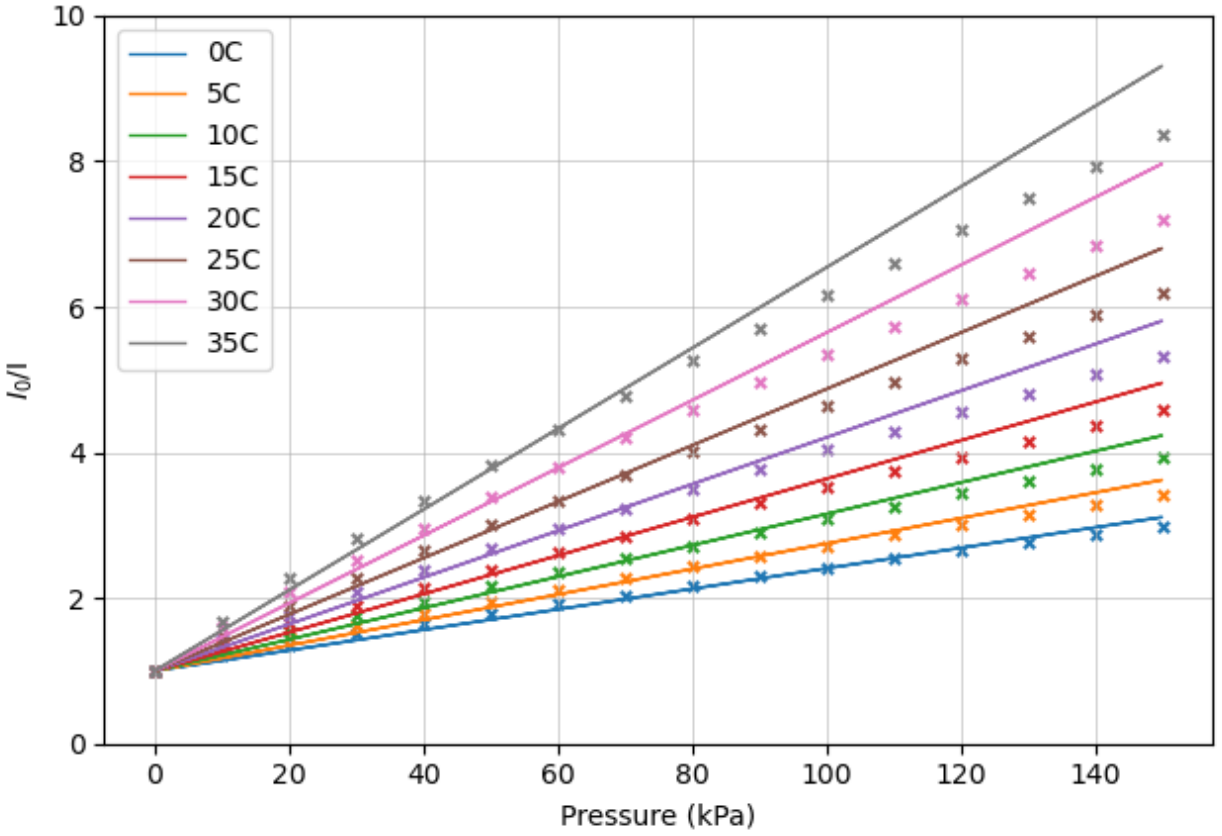
- Coupon is painted along with model, coupon tested in laboratory to generate paint calibration
  - High order polynomial fit may require dozens of T,P data points
  - Coupon and model usually behave differently
  - Produces single paint calibration – paint on model is spatially nonuniform

New paint cal method (in-situ, spatially varying)

- 'Two-response' paint model
- Paint calibration obtained from in-situ pumpdown (wind off, varying pressure) measurements
  - Reduced order model requires ~5 pumpdown data points
  - Produces a paint calibration for every point on model

Paint Calibration Process

Single response calibration and fit



$k_q = 793\ \mathrm{kPa^{-1}\mu S^{-1}}$, $\tau_0 = 3.08\ \mu S$, $k_T = 3296\ K$

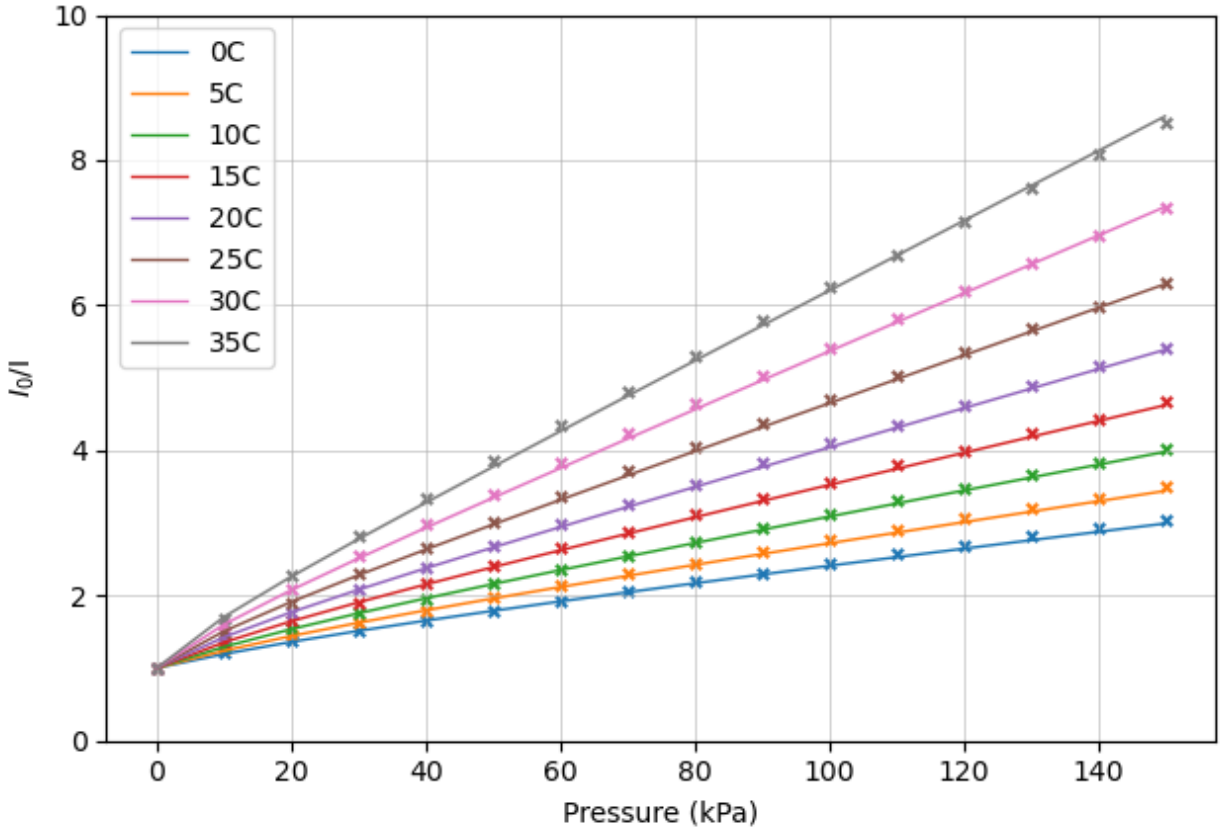
Stern-Volmer Relationship
(with Arrhenius temperature dependence)

$$\frac{I_0}{I} = \frac{\tau_0}{\tau} = 1 + K_{SV}[O_2]$$

$$\frac{I_0}{I} = \frac{\tau_0}{\tau} = 1 + k_q e^{-\frac{k_T}{T}} \tau_0 P$$

Paint Calibration Process

Two-response calibration and fit



Two-response
(Superimposed Stern-Volmer Relationships)

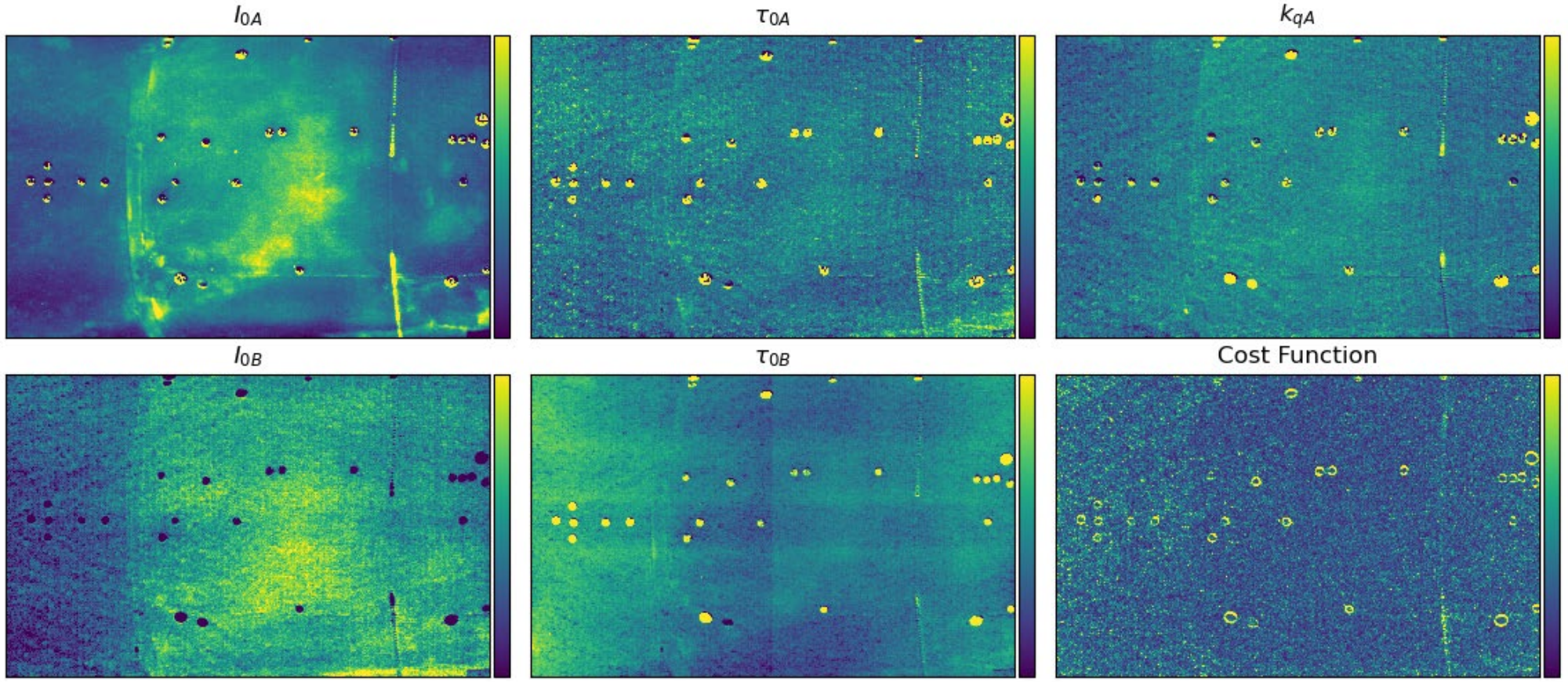
$$I = \frac{I_{0_A}}{1 + k_{q_A}\, e^{-\frac{k_T}{T}}\, \tau_{0_A}\, P} + \frac{I_{0_B}}{1 + k_{q_B}\, e^{-\frac{k_T}{T}}\, \tau_{0_B}\, P}$$

$$\tau_A = \frac{\tau_{0_A}}{1 + k_{q_A}\, e^{-\frac{k_T}{T}}\, \tau_{0_A}\, P}$$

$$\tau_B = \frac{\tau_{0_B}}{1 + k_{q_B}\, e^{-\frac{k_T}{T}}\, \tau_{0_B}\, P}$$

$I_{0_A} = 0.52$, $k_{q_A} = 1048\ \mathrm{kPa^{-1}\mu S^{-1}}$, $\tau_{0_A} = 2.79\ \mu S$,
$I_{0_B} = 0.48$, $k_{q_B} = 2504\ \mathrm{kPa^{-1}\mu S^{-1}}$, $\tau_{0_B} = 6.47\ \mu S$, $k_T = 3552\ K$

Spatial Variation of Paint Calibration



Pumpdown data points taken from Ames 11ft Launch Vehicle Demo Test

- 5 Gate1 + 5 Gate2 images used to fit 5 parameters (assumed $k_T = 8000$ K, $k_{q_B} = 0$)

Simplified 'two-response' paint model applied to every pixel

PRNU, Periodic Noise effects are noticeable

- Future work to implement flatfielding, notch filtering

PSP Steady Acquisition Mode

Steady-state (time mean) PSP uses the 'lifetime method'

- Cameras measure of paint decay lifetime using pulsed excitation
  - Gate1: Lamp ON, Gate2: Lamp OFF, R_L: Lifetime Ratio Gate2/Gate1
- Provides the steady pressures required for 'intensity method'

Steady PSP Shot Noise and Read Noise Error Propagation

$$P = P(R_L, T) \text{ where } R_L = \frac{DN_{Gate2}}{DN_{Gate1}}$$

$$Var(P) = \left(\frac{\partial P}{\partial R_L}\right)^2 Var(R_L)$$

$$Var(P) = \left(\frac{\partial P}{\partial R_L}\right)^2 \frac{{R_L}^2}{\mathrm{DN}_{gate1}}\left[G_c + \frac{Var(\mathrm{DN}_{read})}{\mathrm{DN}_{gate1}}\right]\left(1 + \frac{1}{R_L}\right)$$

- In our application, we average over thousands of frames. Error dominated by bias errors, not random errors

PSP Unsteady Acquisition Mode

Unsteady Pressure-Sensitive Paint (uPSP) uses an 'intensity method'

- Cameras measure paint luminescence in response to continuous excitation
- Processed into fluctuating component of pressure. Determining paint gain G_p requires steady pressures to be obtained separately.

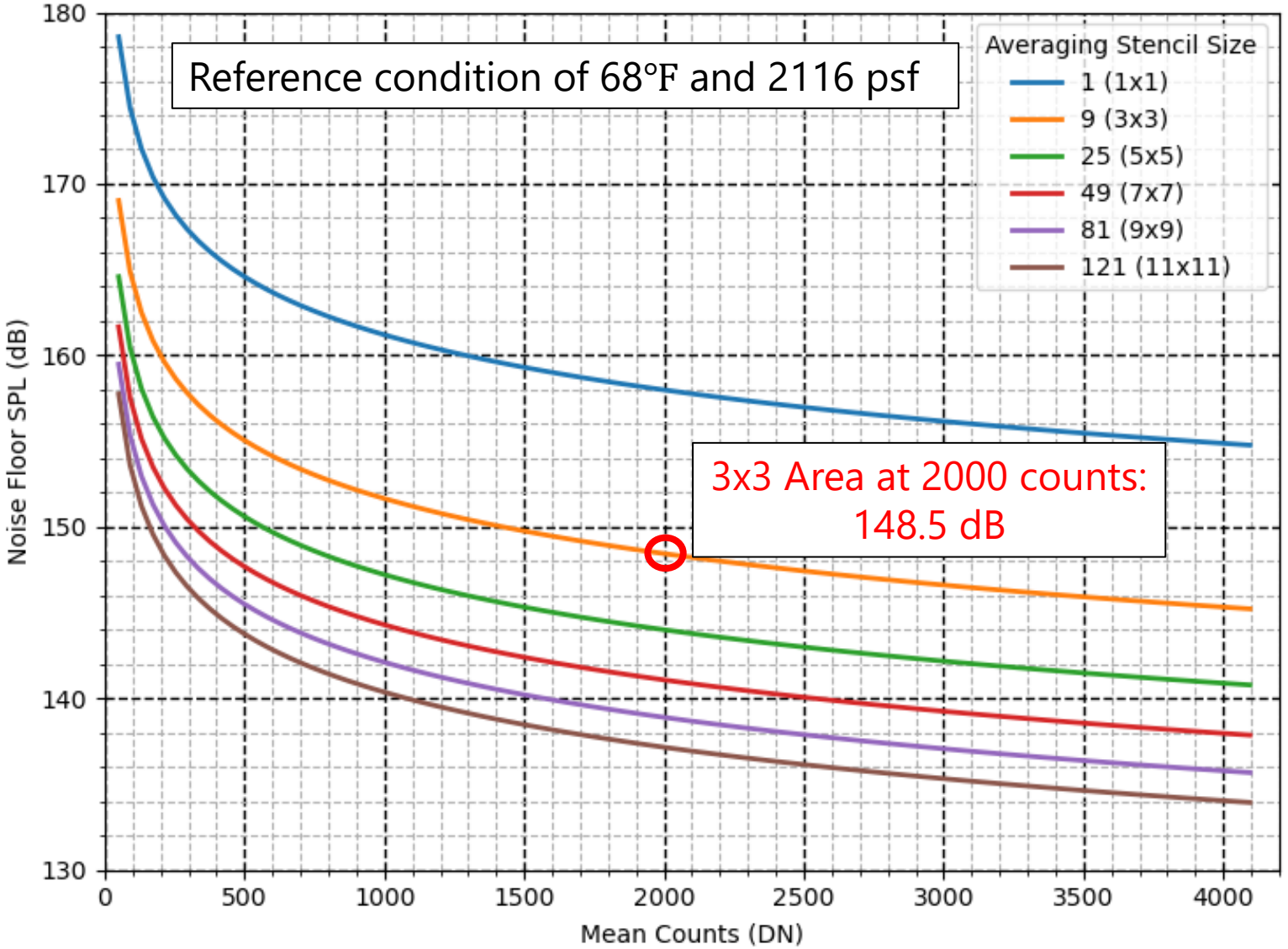
Unsteady PSP Shot Noise and Read Noise Error Propagation

$$\Delta P = G_p \left(\frac{DN_{mean}}{DN} - 1 \right)$$

$$Var(\Delta P) = \frac{G_p^2}{DN_{mean}{}^2} Var(DN)$$

$$Var(\Delta P_{noise}) = \frac{G_p^2}{DN_{mean}{}^2} (G_c DN_{mean} + Var(DN_{read}))$$

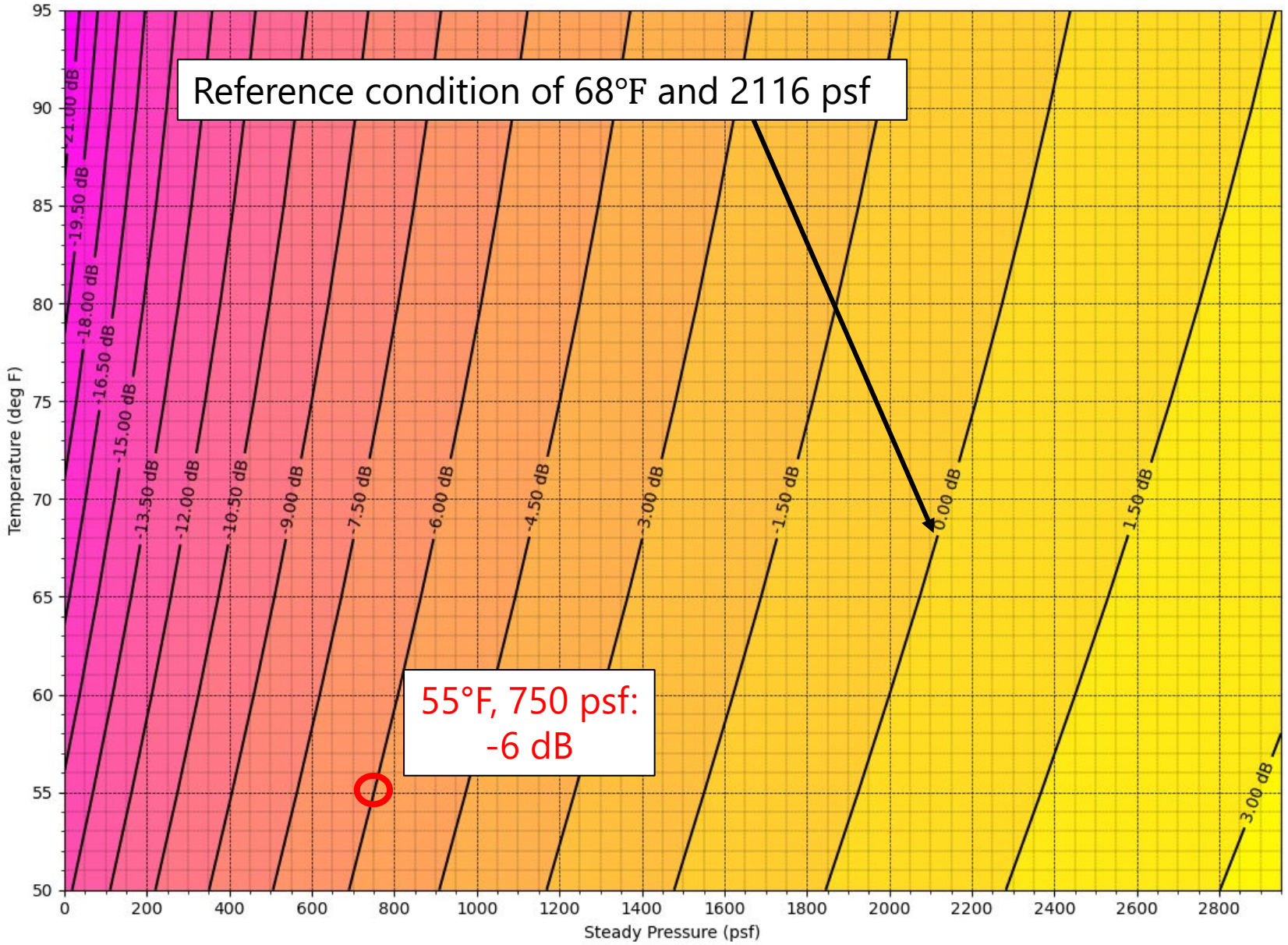
Noise Maps



To adjust for different T, P:

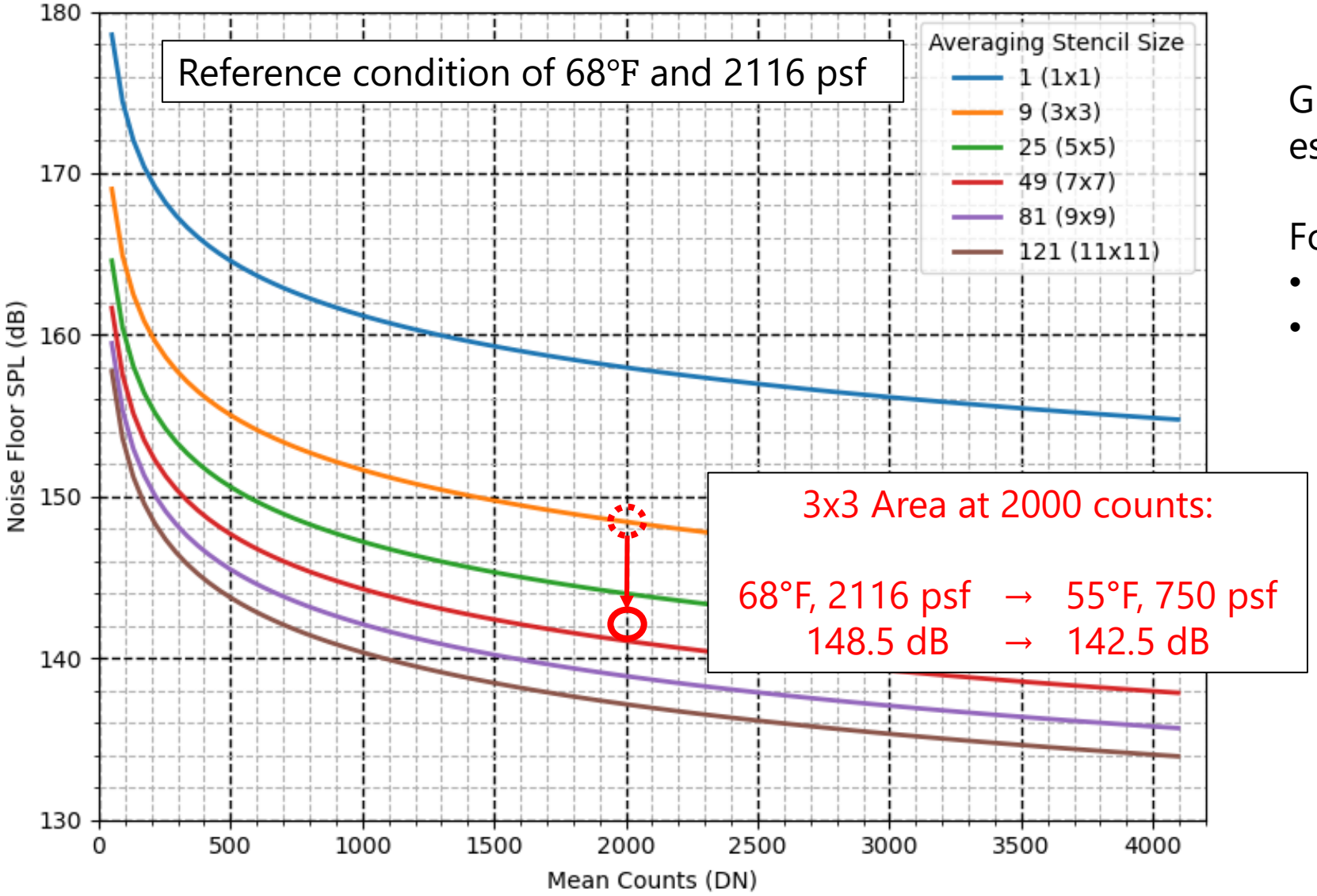
$$Var(\Delta P_{noise}) = \boxed{G_p^2} \times Var(\Delta P_{noise,ref})$$

Noise Maps



Plot of G_p^2 rescaled for SPL

Noise Maps

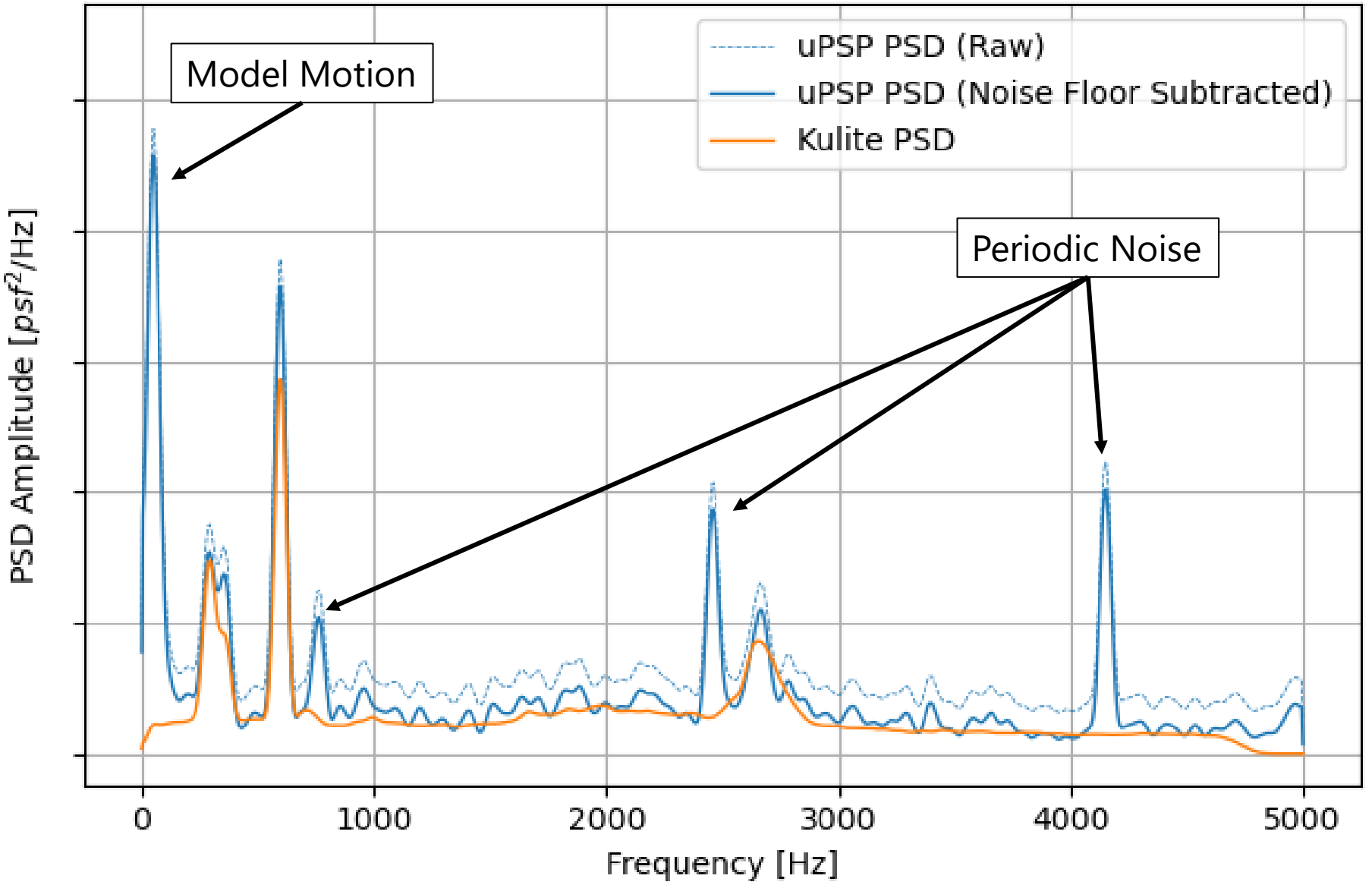


Graphical, intuitive method of estimating noise floor

Formulas would be implemented in:

- spreadsheets (test planning)
- data acquisition software (data quality monitoring)

Comparison to wind-on data



Sample Data Point
from Ames LVDT Test

Conclusions and Summary

New method for noise estimation for test planning and data quality checks

- Developed analytical methods for unsteady and steady PSP error estimation
  - Camera and paint characteristics → noise floor, RMS pressure error
- Developed ‘two-response’ paint model
  - Enables in-situ, spatially varying paint calibrations
- Presented graphical ‘noise maps’ to demonstrate noise floor behavior
- Applied technique to sample wind-on data

Thanks to AETC, SLS, Ames UPWT and Fluid Mechanics Laboratory

Questions?