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Pressure-Sensitive Paint

Experimental Techniques:

Optical surface pressure measurements using luminescent coatings

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Introduction: Pressure Measurements

Pressure measurements are the primary measurements made in most practical aerodynamic testing or basic fluid mechanics experiments. Surface pressure measurements are used for:

- Identifying specific flow phenomena (boundary layer separation, shock wave impingement, etc) that are not easily measured by “standard pressure tap” measurements
- Validation of computational codes
- Loads calculations by integration of the surfaces pressures

Introduction: Pressure Measurements

Conventional pressure measurements: Transducers or taps

- Discrete pre-determined locations
- Very high accuracy (< 0.05% FS)
- Well understood with long testing background
- High data channel throughput with scanned systems (1000+)
- Limitations to were they can be installed
- Expensive installation costs

Introduction: Pressure Measurements

Luminescent coatings:

- Sprayed over entire exterior surface
- Lower accuracy
- Newer method that is still being fully explored
- Resolution limited by detection system
- Limited to optical access applications
- Inexpensive application costs
- Relatively expensive initial costs (approx. the same as multiplexed scanned pressure port systems: ESP/Scanivalve)

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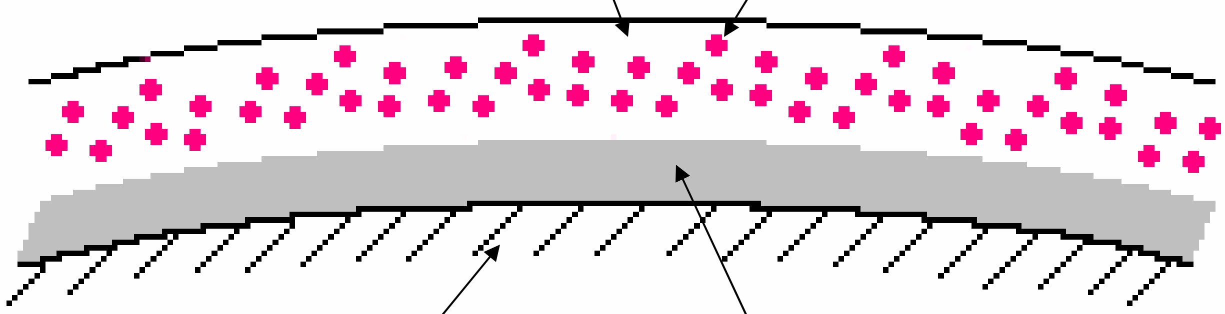
Basic Principles: Anatomy

Oxygen permeable binder ~ 10µm (polymer, silicone rubber or porous solid)

Luminescent Molecules (Ruthenium complexes, Metal porphrins)



Model surface

Undercoat scattering layer ~15µm

Basic Principles: Luminescent Process

- The absorption of light energy by the luminophore can be approximated by the Beer-Lambert law which depends on the illumination intensity, luminophore depth, effective absorption cross-sectional area and luminophore concentration.

- After absorption, there are several excited states that a luminophore molecule can occupy. (Jablonski energy-level diagrams: see references)

- The molecule can return to the ground state through emission (fluorescence or phosphorescence) or quenching

Basic Principles: Luminescent Process

In the presence of oxygen, the molecules can lose their luminescence by transferring their absorbed energy to the oxygen molecule where it becomes vibrational energy. This process is called **Quenching**. Likewise, as temperature increases, the molecules can lose part of the absorbed energy through non-radiative decay, this is highly binder specific. (That is, everything has some kind of temperature sensitivity.)

Basic Principles: Luminescent Process

- For quenching, the intensity decrease is described by the well-known Stern-Volmer equation:

$$\frac{\tau_0}{\tau} = 1 + K_{SV} Q \qquad \text{or} \qquad \frac{\tau_0}{\tau_{\mathrm{O}_2}} = \frac{I_0}{I_{O_2}} = 1 + K_{SV} P_{O_2}$$

Where:

τ is the lifetime, I is the intensity

K_{SV} is the Stern-Volmer constant

Q is the quencher or partial pressure of oxygen

Basic Principles: Luminescent Process

• The Stern-Volmer equation is rewritten in the popular intensity ratio form:

$$\frac{P}{P_{REF}} = A + B\frac{I_{REF}}{I}$$

• A and B are highly dependent on the luminophore and binder material as well as the temperature sensitivity of the materials used to make the paint. A 2^{nd} order curve generated from calibration data is most often used.

Measurement Methods/Systems

- Intensity based Methods (most common)
  - Full-field using camera
  - Point systems using scanning laser
- Time based Methods (lifetime decay)
  - Full-field using camera
  - Point systems using scanning laser
- Frequency based Methods (phase shift from excitation)
  - Full-field using camera
  - Point based system using scanning laser

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Intensity Methods

- Requires two readings, a reference at constant pressure (wind-off) and an unknown data point (wind-on)
- Ratio of intensities I_{REF}/I is inversely proportional to the air pressure
- The excitation and detection systems must be spectrally separated, (>10^{-6} attenuation in stop band)
- Simplest technique, most sensitive
- Very sensitive to motion between wind-off and wind-on
- A long period of time can elapse between reference and data images resulting in significant changes in contamination of paint, light stability, etc that cannot be normalized by the reference condition.

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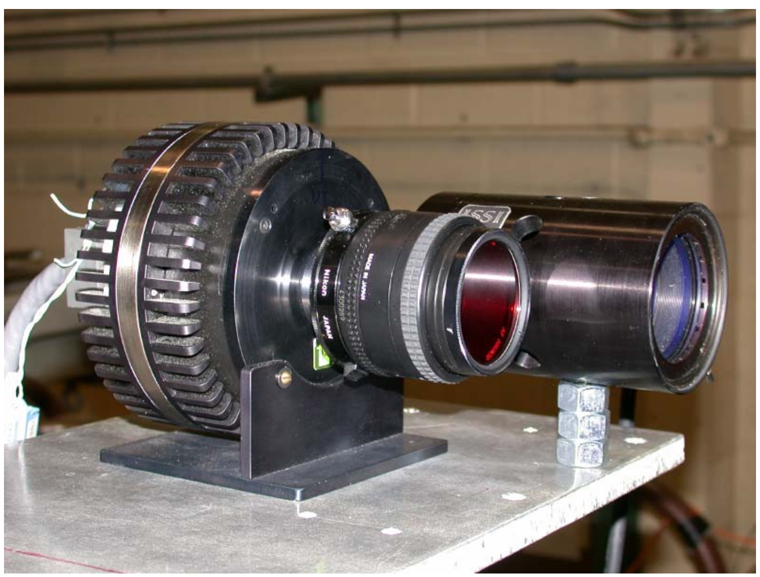
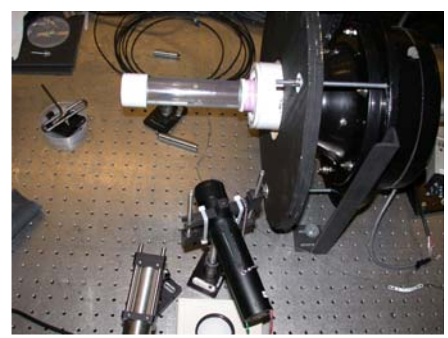
Intensity Methods

- Excitation:
  - Continuous Sources: LEDs, Filtered lamps (Halogen, Xenon), Lasers
  - Pulsed Sources for instantaneous or periodic measurements: LEDs, Xenon strobes/flash



- Detectors
  - Cooled Scientific grade CCD cameras (slow scan, low noise), PMT, PD



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Intensity Methods: Types of Testing

Imaging Techniques

- Most aero data is taken during steady state conditions with constant illumination
- Steady state data extracted from a pulsed synchronization illumination with a periodic experiment (rotating)
- Dynamic data from a pulsed synchronized illumination with a periodic experiment with time delay off of a trigger signal

Point Techniques

- CW laser and PMT to get time history data at a single point both steady and unsteady data
    - Laser can be stationary or scanned

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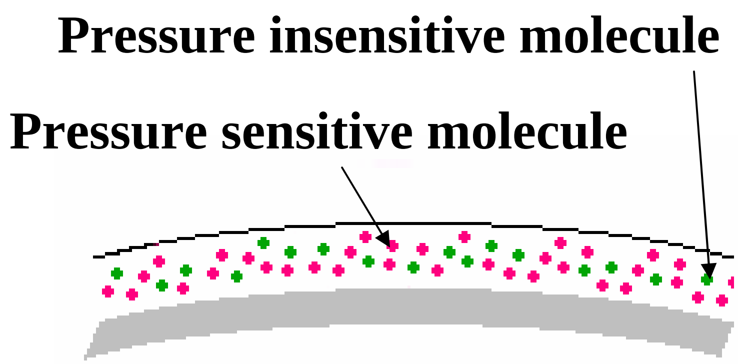
Intensity Method – Dual probe

Self-Referencing paints



Advantages:

Eliminate wind off images and image registration problems. It works in theory but do to homogeneity problems of dispersing two probes equally it actually requires a double set of ratios, often called ratio of ratios method.

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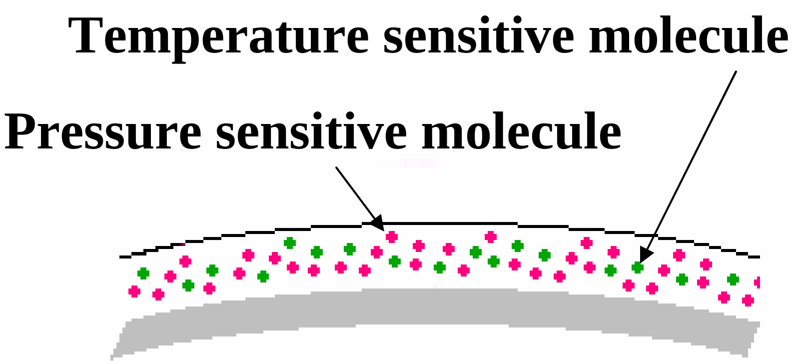
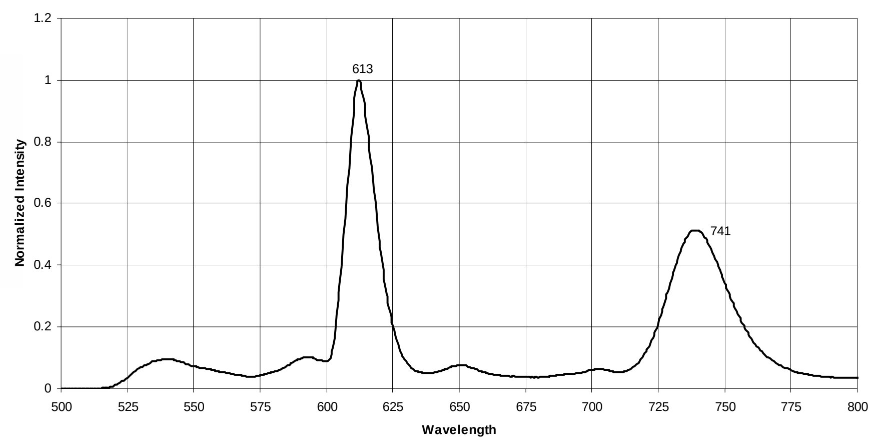
<u>Intensity Method – Dual probe</u>

Pressure - Temperature paints





Advantages:

Measure temperature to compensate for temperature sensitivity of PSP.

This technique requires all four images to be aligned.

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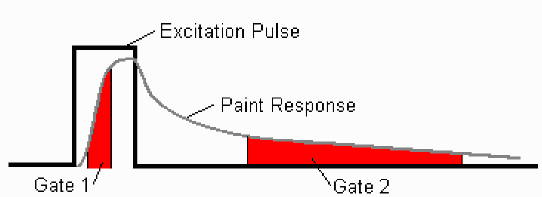
Time-resolved Methods

• Easiest to do with a point measurement, but can use time resolved cameras to measure lifetime decays of the probe molecules.

• Point measurements require a pulsed light source and detector (PMT, PD)

• Time resolved imaging requires a double pulse type experiment to measure the decay times (gated camera, interline transfer camera capable of multiple flash integration).



Luminescent lifetime τ $\tau = f(P, T)$

$P = a(G1/G2)^2+b(G1/G2)+c$:imaging case

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Time-resolved Methods

Benefits:

• Eliminates the need for aligning two images since the pair of images are taken at the same condition relatively close in time (seconds).

Disadvantages:

• Camera noise is much higher, especially gated intensified cameras

• Paints have tended to be more spatially noisy from lifetime differences between molecules (homogeneity problem).

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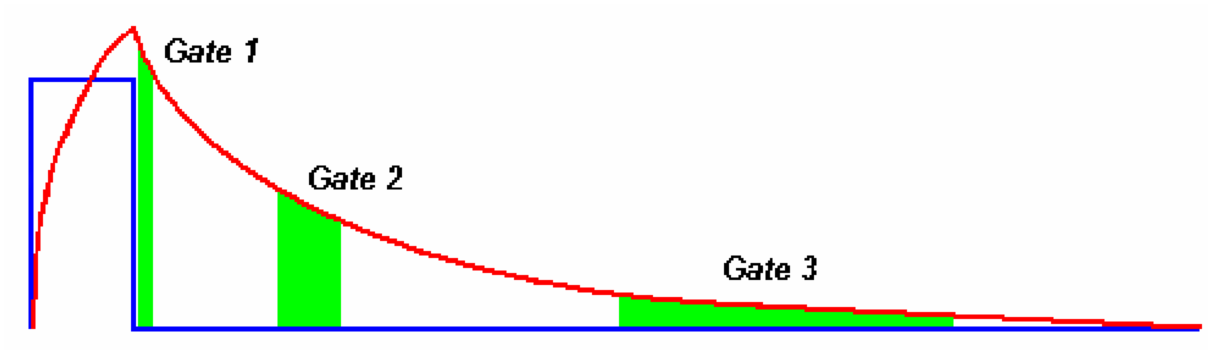
Time-resolved Methods

Determination of pressure and temperature from a single probe

- The time decay signal has embedded temperature and pressure information

- Requires three gates to generate two equations of gate ratios to solve for pressure and temperature at each point (pixel)

- Significant processing for imaging applications



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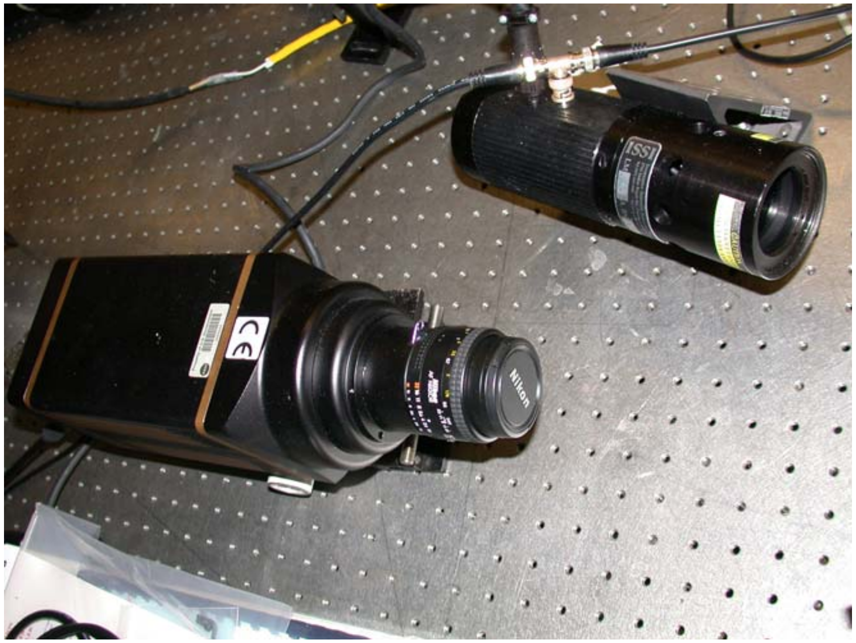
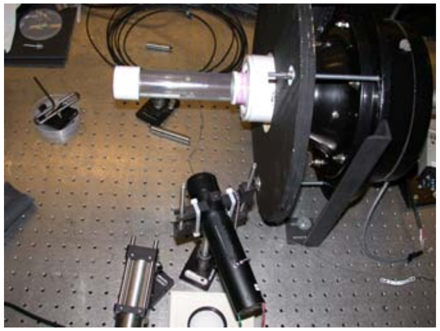
Time-resolved Methods



Cooled intensified camera and pulsed LED

Cooled interline transfer camera



Pulsed laser and PMT

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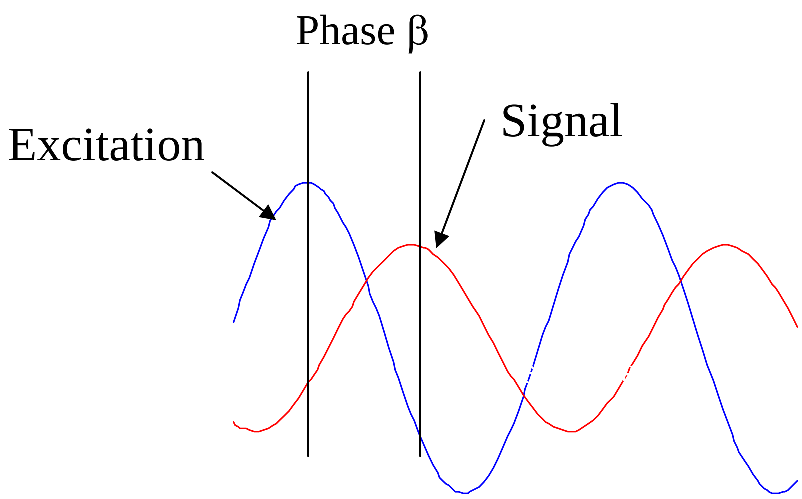
Frequency-resolved Methods

- If modulation frequency is fixed, then the phase angle β is a function of the lifetime $\tau = f(P,T)$
- Phase angle can be measured directly with a lock-in amplifier
- Phase delay can be measured using two images from a camera locked in phase to the excitation, the second image is acquired out of phase



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Coatings

• Must combine durable physical properties (ease of application and removal, adhesion, cure time, hardness, abrasion resistance, surface finish, thickness, etc) with correct photo-physical properties (absorption and emission properties, pressure and temperature sensitivity, time response, quantum efficiency, photo-stability, etc)

• The two main probes used are: (Platinum porphyrins and Ruthenium complexes), quenching characteristics when combined with binder work well for the range of pressures and temperatures typically encountered in aero testing

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Coatings

- PSP coatings used at NASA GRC
  - Boeing PF2B – ruthenium bathophenanthroline in silicone rubber binder (soft paint, chlorinated solvent)
  - UW (ISSI) FIB – PtTFPP in FIB copolymer binder (hard, good steady state paint)
  - NASA Langley – PtTFPP in FEM (very hard, very smooth finish)
  - ISSI sol-gel – Ru(ph_2-phen) and PtTFPP on sol-gels (higher frequency response)
  - Anodized aluminum – dip coated Ru(ph_2-phen) on anodized surface (very high freq. response)
  - UW PtOEP in MAX acrylic copolymer (ice paint)
- TSP coatings used at GRC
  - Boeing TSP (range: 0 to 100°C, sensitivity ~ -3%/°C)
  - EuTTA in commercial clear or shellac (-20 to 80°C, ~ -4%/°C)
  - Thermographic phosphors in high temp binders (-20 to >1000°C)

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Data Reduction- Imaging

- Multi-step process
  - Converting light intensity measurements in the image plane to pressures (CCD corrections)
  - Correct for real-world effects (motion, temperature, etc)
  - Calibration
  - Mapping image plane to model plane
- Custom or commercial software is available

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Data Reduction: Image Corrections

- Although CCDs are excellent light detectors, corrections need to be made:
  - Tare correction - CCD bias, dark charge, background lighting
  - Flat-field correction – corrects for non-uniform response in pixel elements
  - Image summation – summing N images effectively increases the detector charge well capacity by N and SNR by $\sqrt{N}$ but at the expense of longer data acquisition times
- Image registration – test article moves with respect to the camera in almost every case
  - Registration targets on the model surface are used to calculate corrections
  - Movements can be simple X-Y translation or multi-order warping

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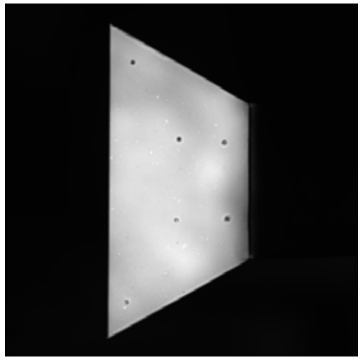
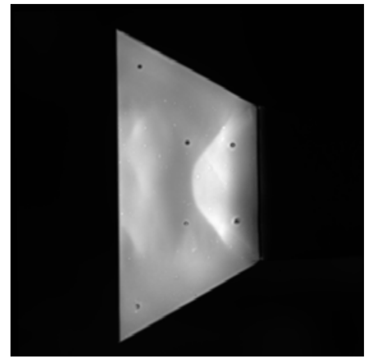
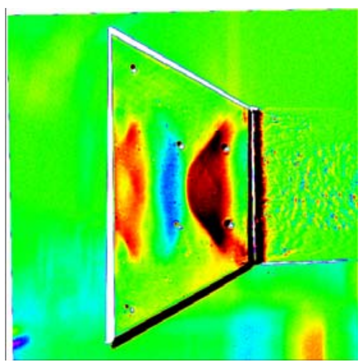
Intensity Method



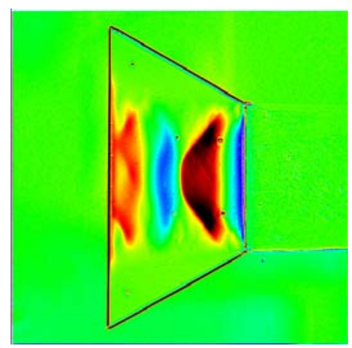


Wind-off **Wind-on**

Image Registration



Ratio



Unregistered Images **Registered Images**

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Data Reduction: Calibration

- A-priori Calibrations
  - Paints are typically calibrated in a cell that varies pressure and temperature and has a reference measurement – this calibration is used when no on-model instrumentation exists
- In-situ Calibration
  - Uses standard on-model instrumentation to calibrate the paint/images in place
  - Compensates for temperature differences from reference data, spatial temperature differences are averaged among all the points used to generate a calibration
- In practice both calibrations are typically used

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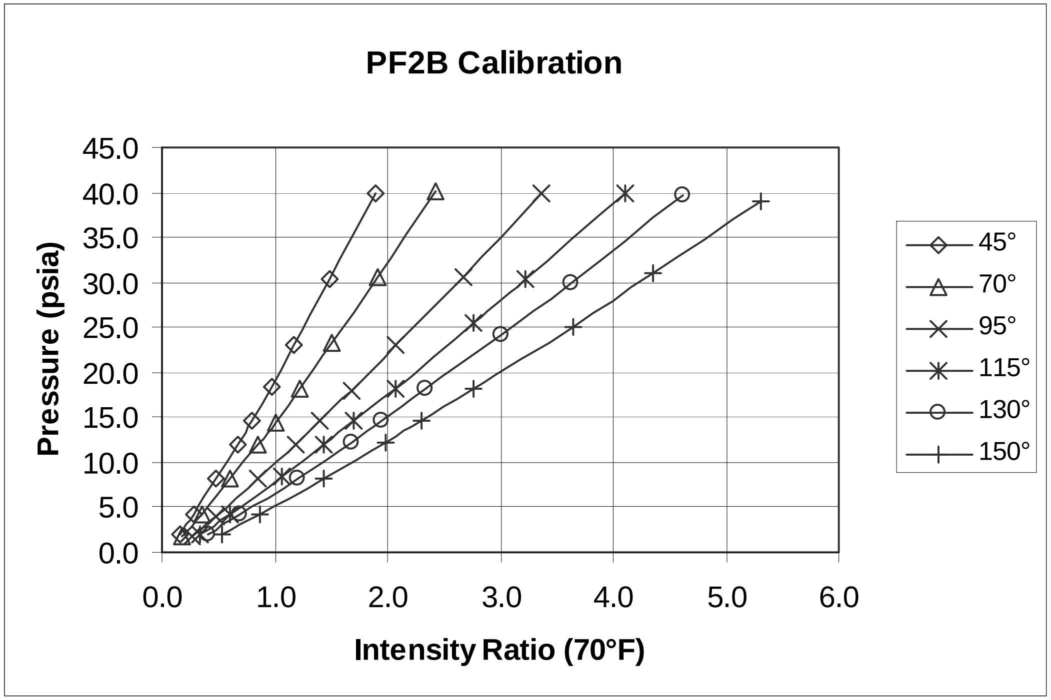
Data Reduction: Calibration



A typical PSP calibration for pressure and temperature

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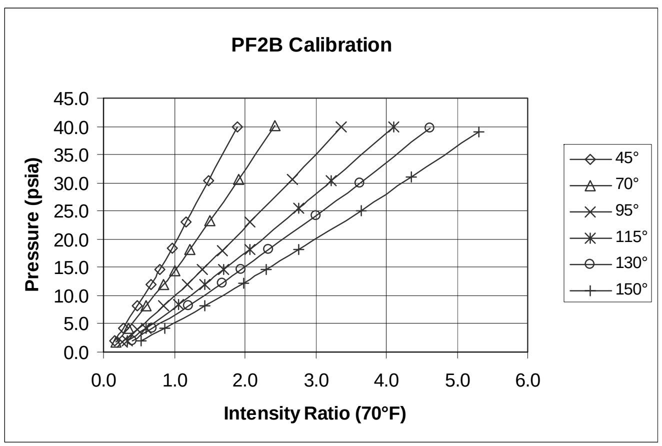
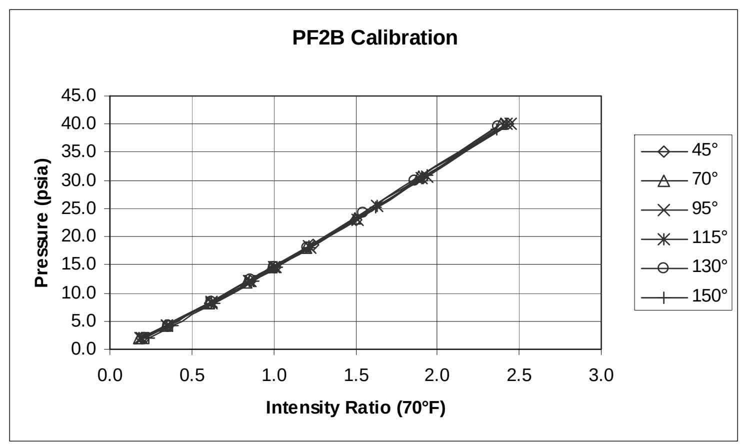
Data Reduction: Temperature Compensation

- Spatially distributed large temperature differences give significant errors
  - Generated by jets impinging on the painted surface, internal plumbing for blowing type experiments, shocks on insulating type materials
- Use calibration data along with TSP images to compensate for temperature variations





Data Reduction: Other Corrections

- Self-illumination: correct for reflections from surfaces that are normal to each other (corner effects of a wing and fuselage)
  - Solved as a 3D problem, data must be in model coordinates
- Frequency response corrections: must know the attenuation of the coating to a fluctuating pressure, paint thickness dependent (difficult to correct)
- Illumination compensation: Dual probe or self referencing paints require ratio of ratios technique (because wind-off still needed, these paints have limited advantages)

Data Reduction: Resectioning

- Transform image plane (2D) to model plane (3D) coordinates using photogrammetry techniques for mapping PSP data on to CFD generated grids
- Multiple views allow full 360° views of pressure data to be represented
- Techniques typically based on central projections from the painted model through a optical point to the image plane
- Reference marks on model are measured to give the needed inputs to solve the transformations matrices
    - Colinearity equations of photogrammetry
    - Direct linear transform

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Uncertainty

- Characterization of the paint and calibration errors (a-priori, in-situ calibration, photodegradation, paint contamination, paint intrusiveness, time response)
- Measurement system errors (detector noise, illumination spectral and temporal stability, spectral leakage)
- Signal analysis errors (registration from model motion and deformation, incomplete temperature compensation, self illumination, resectioning on a non-deformed grid)
- The major contributor is temperature uncertainty which can account for up to 90% of the total uncertainty