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On the Use of Hot-Film Sensors in the Investigation of Fluid Dynamic Phenomena in the Near-Wall Region

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Overview

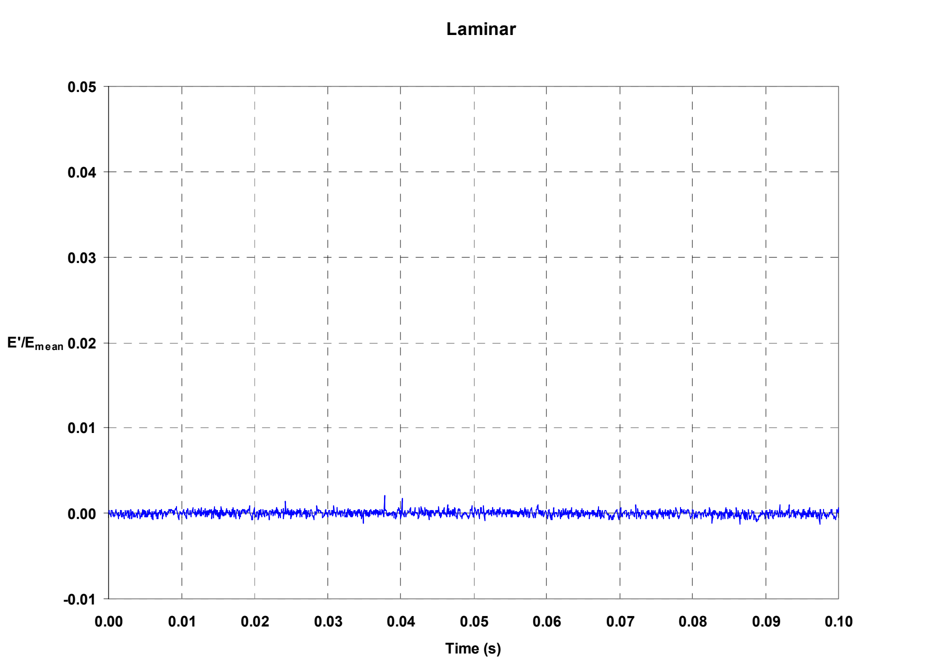
- Introduction and Nature of the Problem:
- Experimental Methods:
  - Test Rig – Subsonic Cascade.
  - Hot-Wire & Film Specifications.
  - Wire-Film Correlation.
- Experimental Results:
  - Correlation between a hot-wire and film operating simultaneously in a turbulent boundary layer.
  - Wavelet analysis techniques.
  - Hot-film surface roughness measurements.
- Conclusions.

Introduction & Nature of the Problem

- Focus is on the physics of the near-wall region.
- From a loss measurement perspective, this region consititutes most of the loss in a turbulent boundary layer due to:

  Viscous Dissipation

  Reynolds Stress Production
- Hot-film sensors respond to velocity fluctuations and can be used to determine the nature of the boundary layer over a surface.
- As turbulent energy is dissipated in the near-wall region by viscosity, theoretically turbulent fluctuations should approach zero at the wall.
- How can sensors that form the wall detect such fluctuations?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0.04
0.03
E'/Emean 0.02
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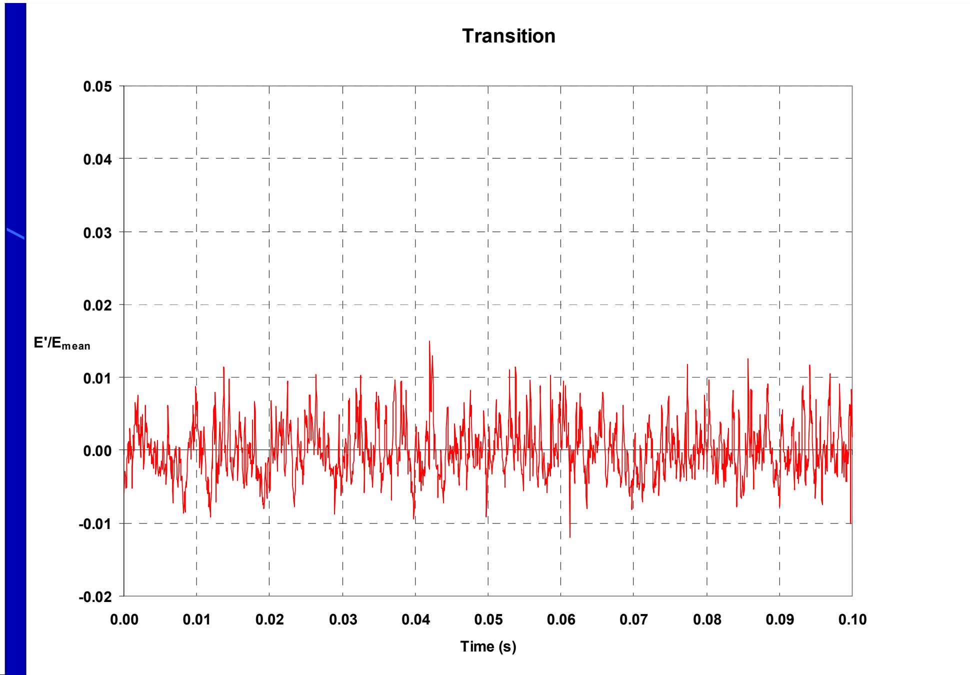
Time (s)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0.03
0.02
E'/Emean
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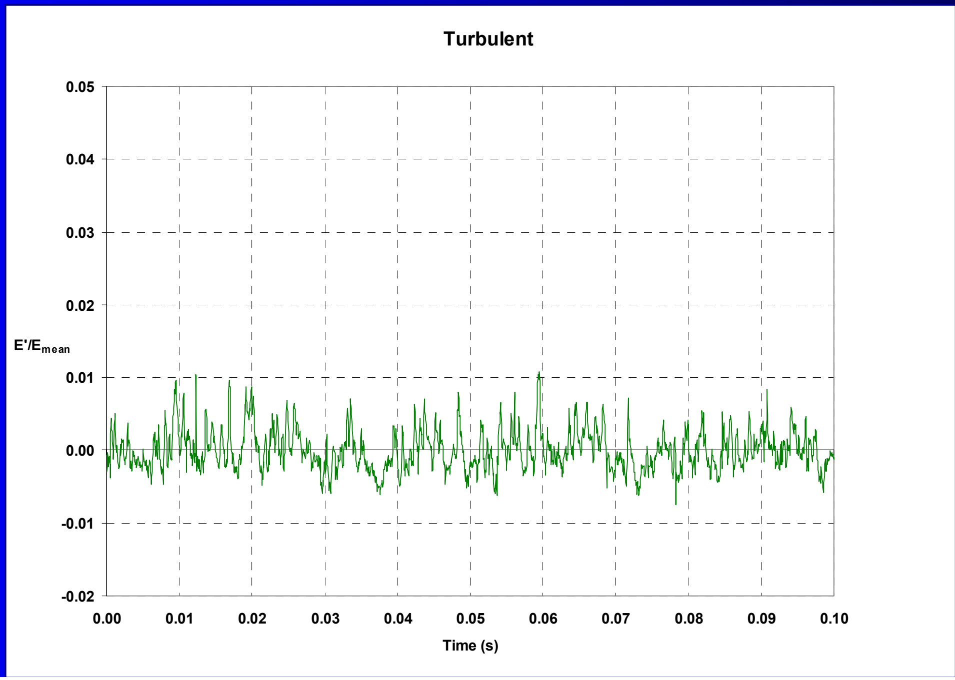
Time (s)


Turbulent
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0.04
0.03
0.02
E'/Emean
0.01
0.00
-0.01
-0.02
0.00 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.10
Time (s)

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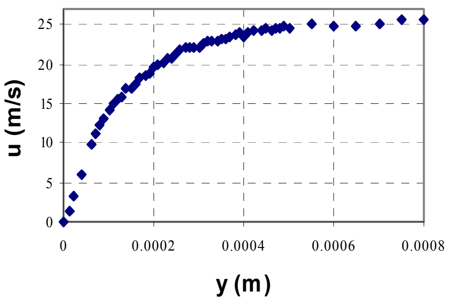

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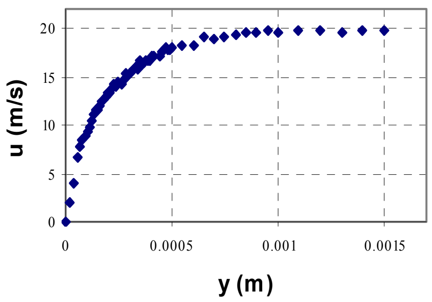

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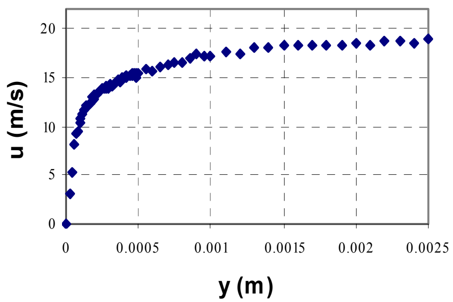

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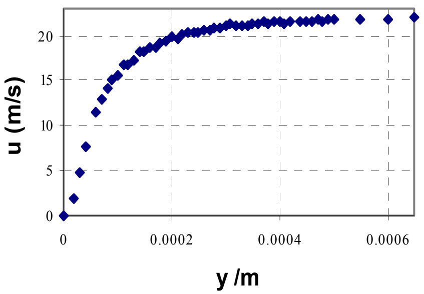

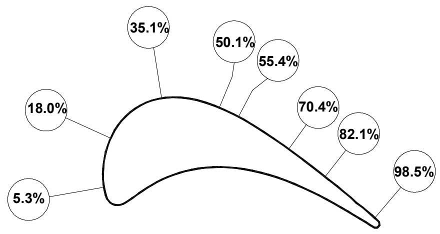

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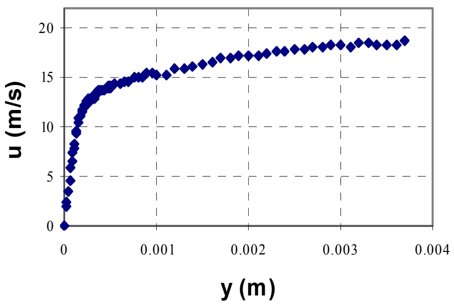
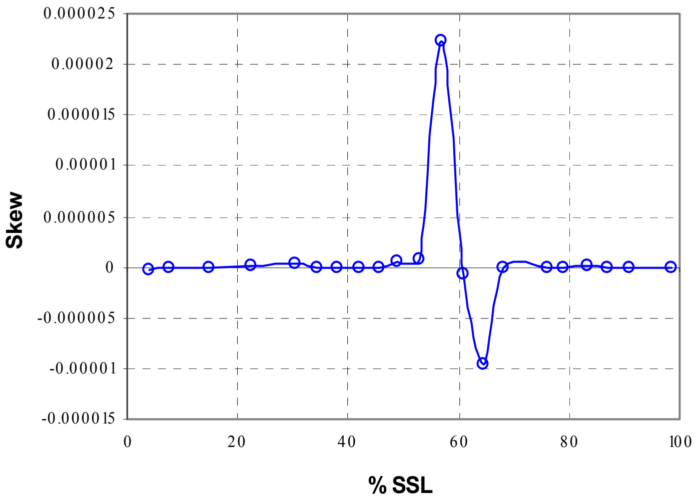


Skew Distribution Derived From Fluctuating Hot Film Voltage Signals



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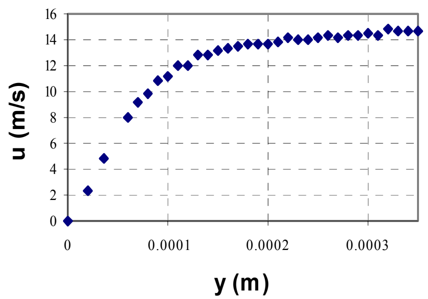
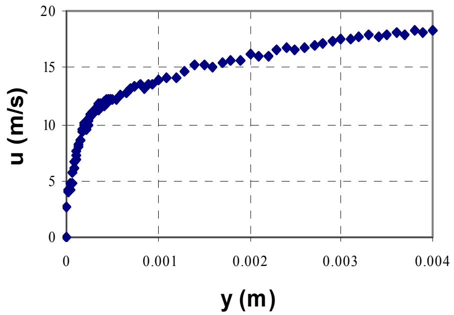


95% SSL

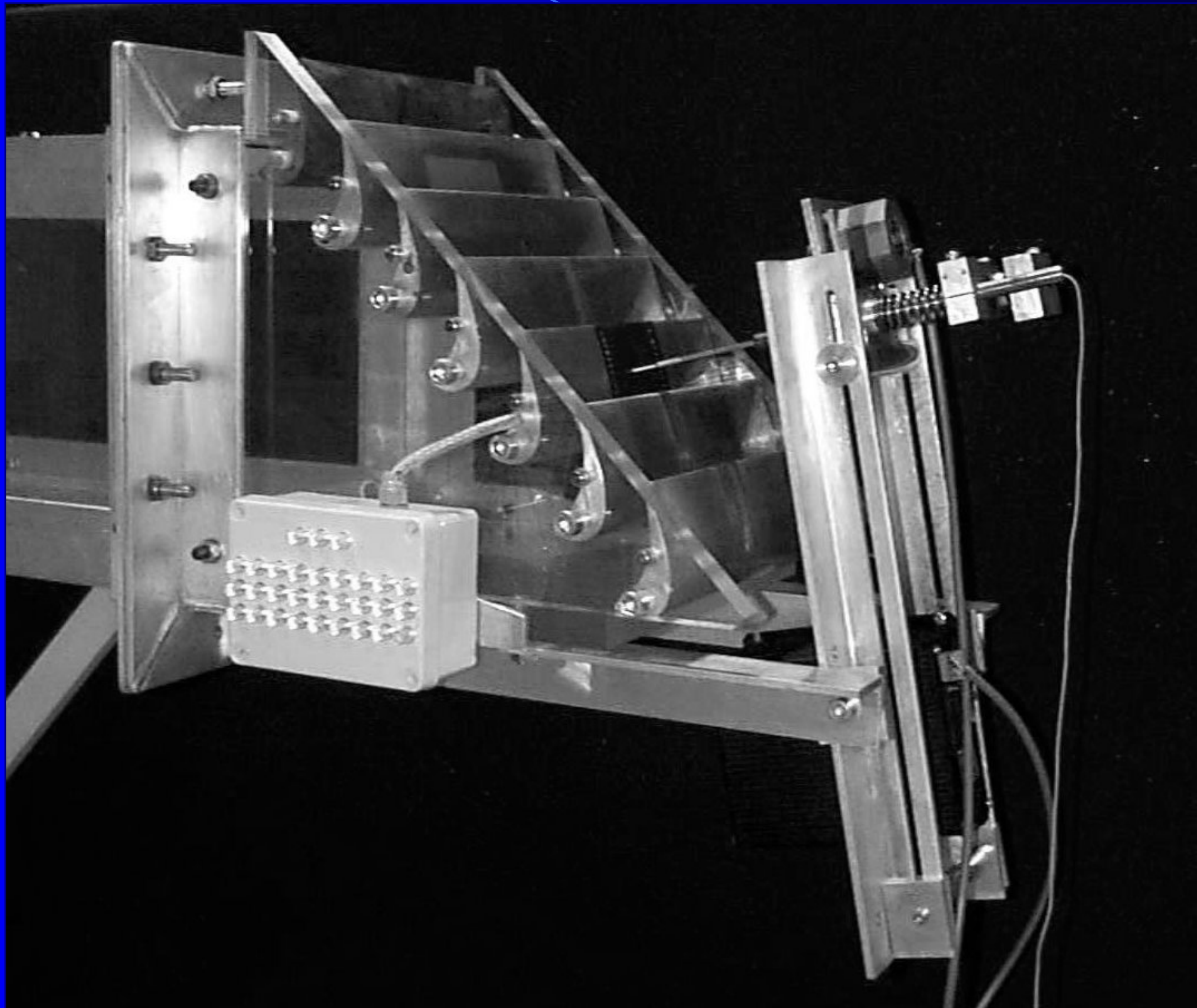


Measured Hot Wire Boundary Layer Velocity Profiles Re_c = 76,000 & 5.2% Free Stream Turbulence

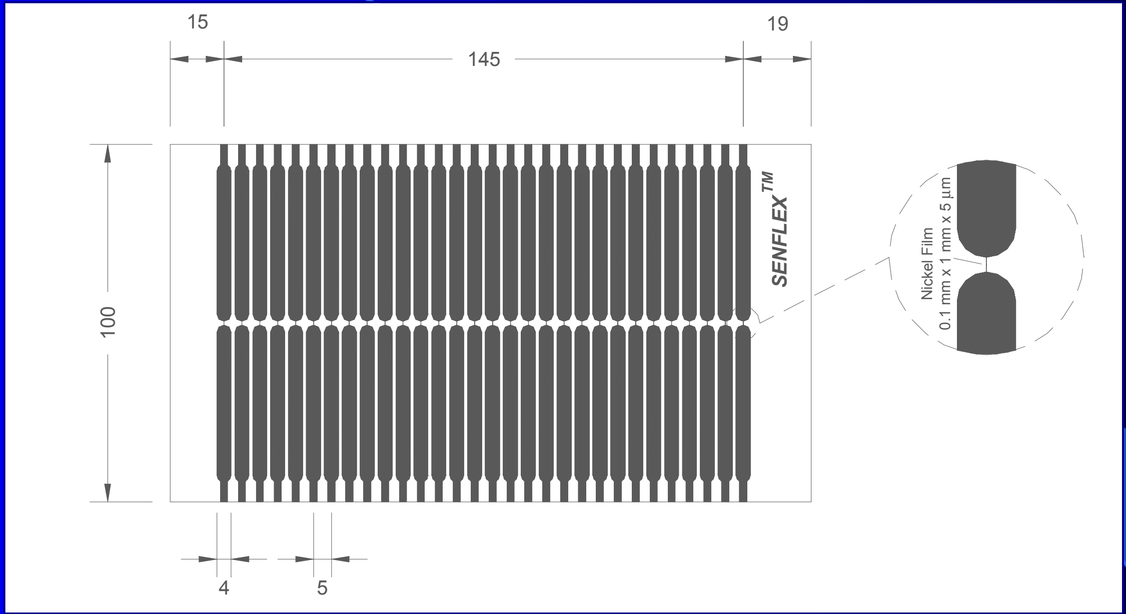
Introduction & Nature of the Problem

- Hot-film sensors should not be sensitive to velocity due to the no-slip condition.
- Classical view - no-slip condition arises due to adsorption of gas molecules onto a solid surface.
- However no surface is perfectly smooth to an atomic level.
- Even the most finely polished surface has roughness elements (asperities) that are substantially larger than the gas molecules.
- Perhaps, the fluid is brought to rest due to the tortous path taken around the roughness elements.
- Will look at surface finish later.

Experimental Methods – Subsonic Cascade



Hot-Film Array Specification



- Sensor elements are manufactured from Nickel and are electrodeposited onto a polyimide substrate.

- Sensor dimensions:

  1.44 mm X 100 μm x 0.2 μm

- Surface finish for electrodeposited materials is typically of the order of 0.02 μm.

Experimental Methods - Wire-Film Correlation

- Correlation between readings from a hot-wire and hot film in the turbulent boundary layer at 76.6% SSL with Re = 76,000 and 5.2% FST.
- Simulataneous operation of a hot film at 130°C and a Dantec 55P11 hot wire probe (250°C) while traversing from 10 μm to 4 mm in the wall-normal direction.
- 20 kHz sampling frequency over 0.1 second duration.
- Physical Significance of the Correlation Coefficient (ρ_{12}):

$$\rho_{12} = \frac{\overline{\left(U_1 - \overline{U_1}\right)\left(U_2 - \overline{U_2}\right)}}{\sigma_1 \sigma_2} = \frac{\overline{u_1' u_2'}}{\sqrt{\overline{u_1'}} \cdot \sqrt{\overline{u_2'}}}$$

- If $\rho_{12} = 1$, then both wire and film are sensing the same phenomenon.
- If $\rho_{12} = 0$, then wire and film are not sensing the same phenomenon.

(statistically independent variables)

Experimental Methods - Wire-Film Correlation

- Operating both a wire and film together poses problems:

  Thermal boundary layers from both wire and film interfere with each other close to the wall.

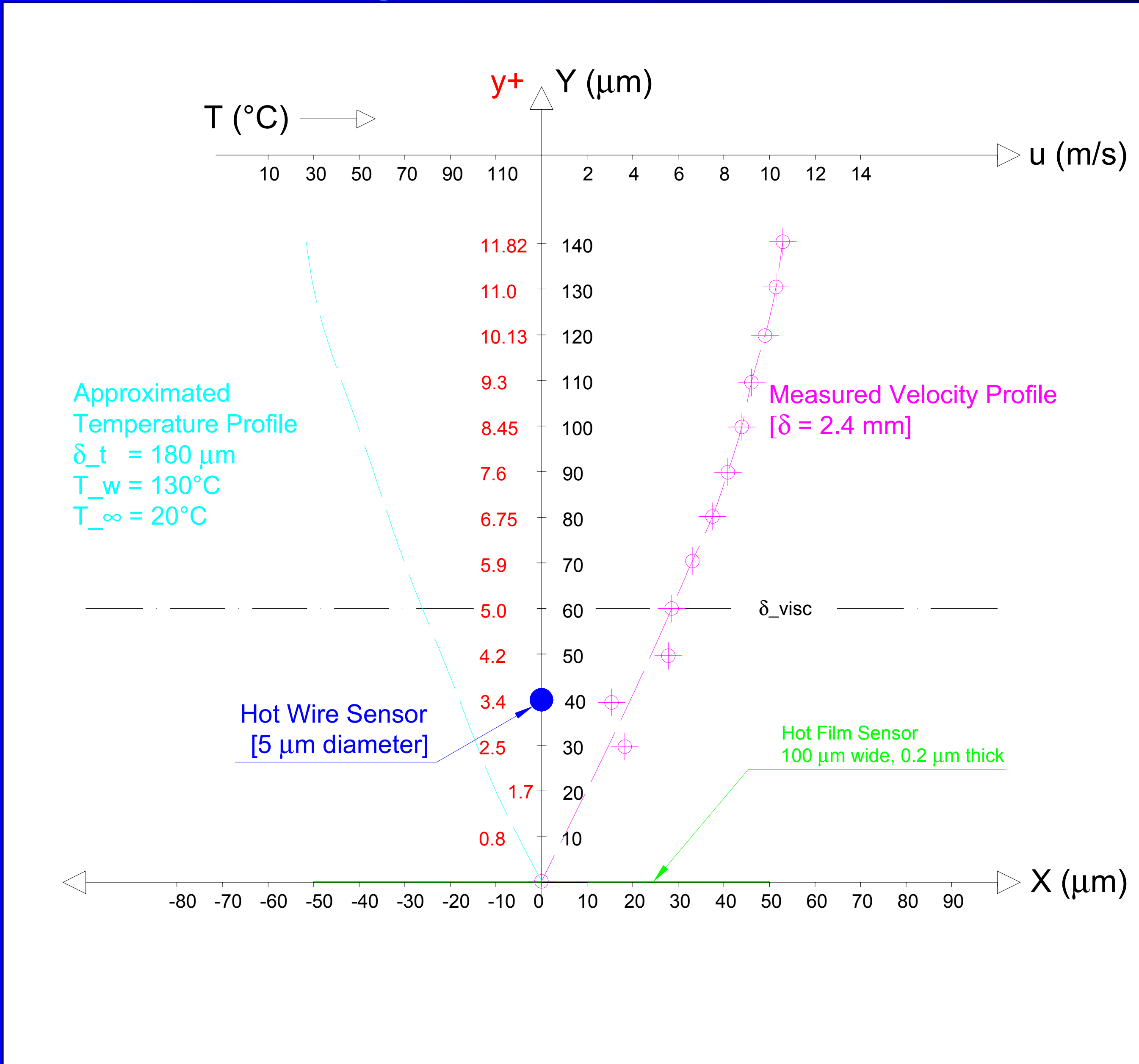
  Therefore inaccurate results will be obtained in this region

  Correction of the hot-wire readings for near-wall effects made difficult.

- δ_t was estimated to be approximately 180 μm, but the effects of the thermal boundary were only prevalent within 60 μm of the wall.

- All data influenced by the thermal boundary layer was neglected.

Scale of the Problem



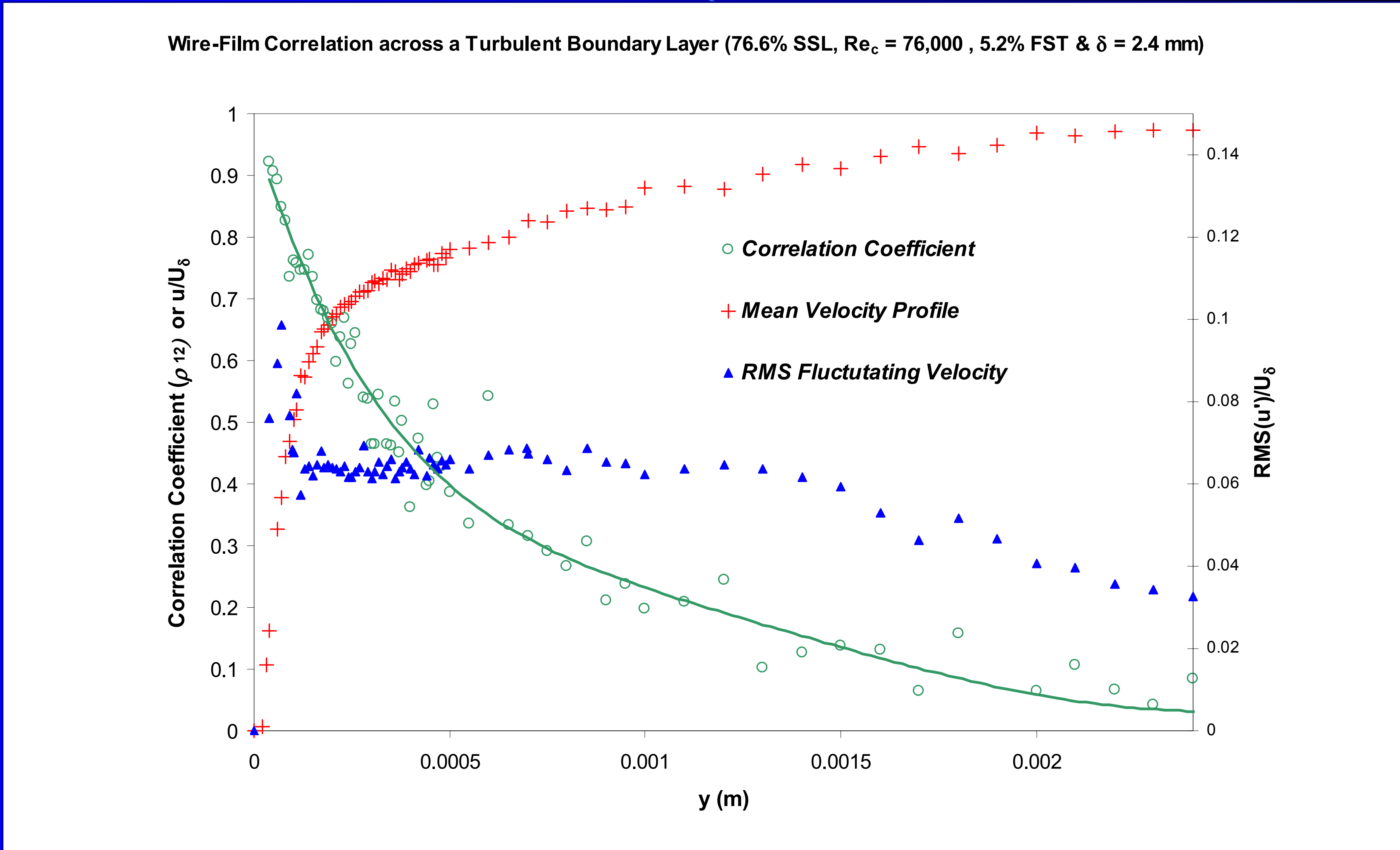
Experimental Results - Summary

1. Wire-film correlation distribution through the turbulent boundary layer at 76.6% SSL, and 5.2% FST.

2. Wavelet analysis of the simultaneously sampled wire and film data.

3. Measurements of the surface roughness of the hot-film sensor using Atomic Force Microscopy (AFM).

Wire-Film Correlation



Wavelet Analysis Methods

- Wavelet methods permit localisation of intermittent data both in frequency and time domain.
- Approach is similar to a Fourier Transform, time series is convoluted with compressed and dilated forms of a detector function known as the "Mother Wavelet" $\psi(t)$.
- The detector function can be any real or complex valued function that satisfies the "Admissibility Criterion" (zero mean).

$$\int_{-\infty}^{+\infty} \psi(t)\, dt$$

- Wavelet is compressed/dilated and time shifted, to yield a matrix corresponding to all times and frequencies in the signal.

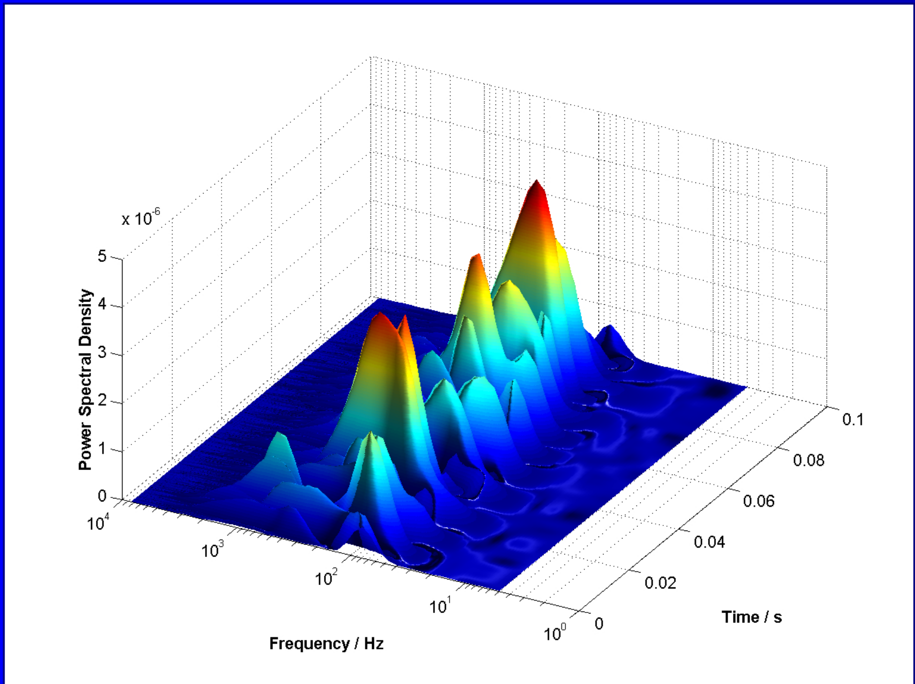
$$\Psi_{(\omega,\tau)}(t) = \frac{1}{\sqrt{\omega}}\,\psi\left(\frac{t-\tau}{\omega}\right)$$

Wavelet Analysis Methods

- Convoluting with time series completes the transform, generating a 3-D time-frequency representation of the signal.
- Choice of Wavelet depends on the application.
- In this study the Marr Wavelet (second derivative of the Gaussian function) was used.
- 41 frequencies (spaced evenly on a log scale from 5-5kHz) were scanned at 2000 time increments from 0 to 0.1 seconds.
- Data was filtered to remove AC mains noise (50 Hz)
- Wavelet transforms and data filtering implemented in MATLAB™

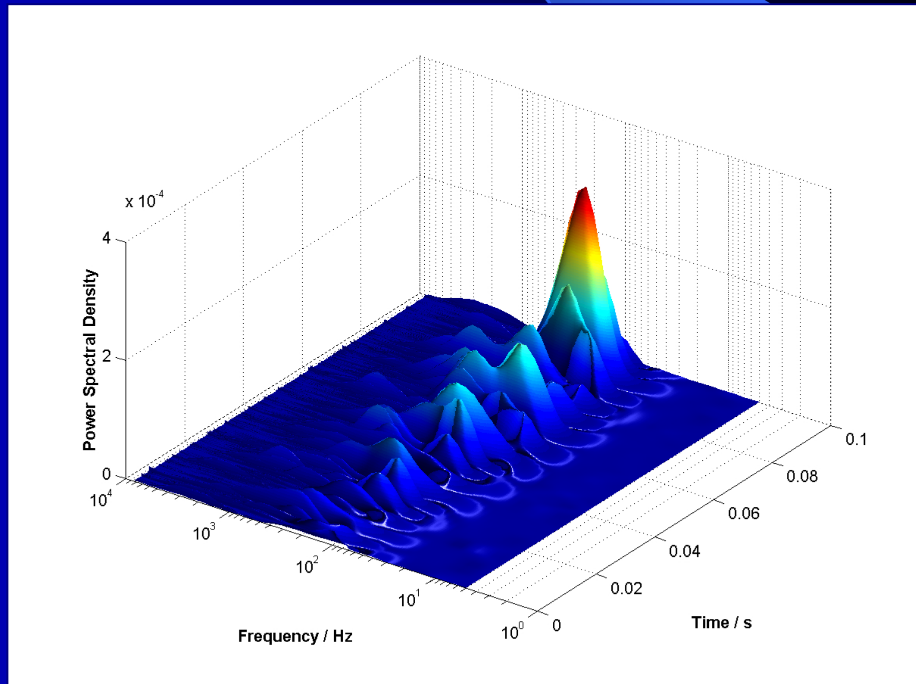
Wavelet Analysis Methods

Simultaneous Wire-Film Signals in a Turbulent Boundary Layer



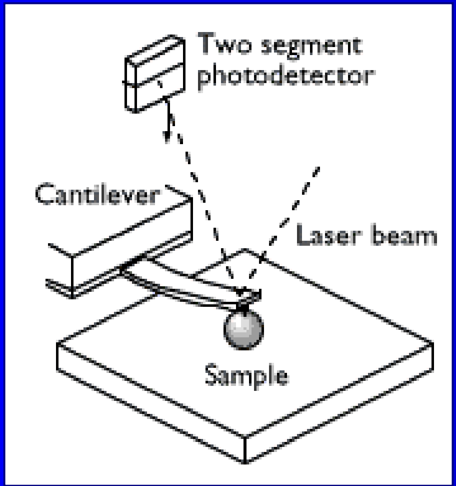
Hot-Film

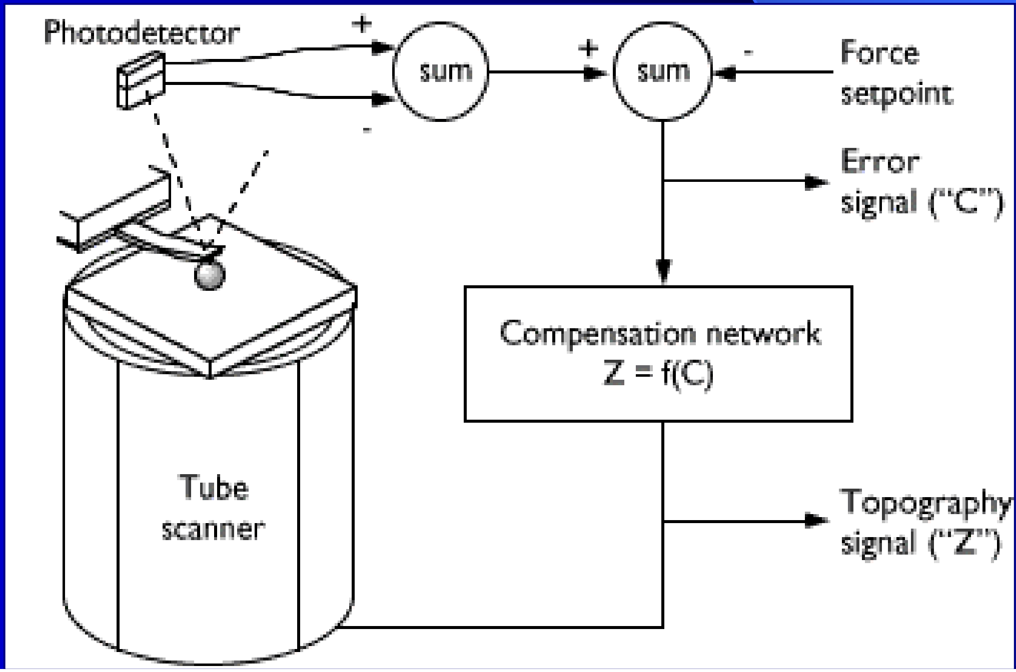
Hot-wire at $y/\delta = 0.1$



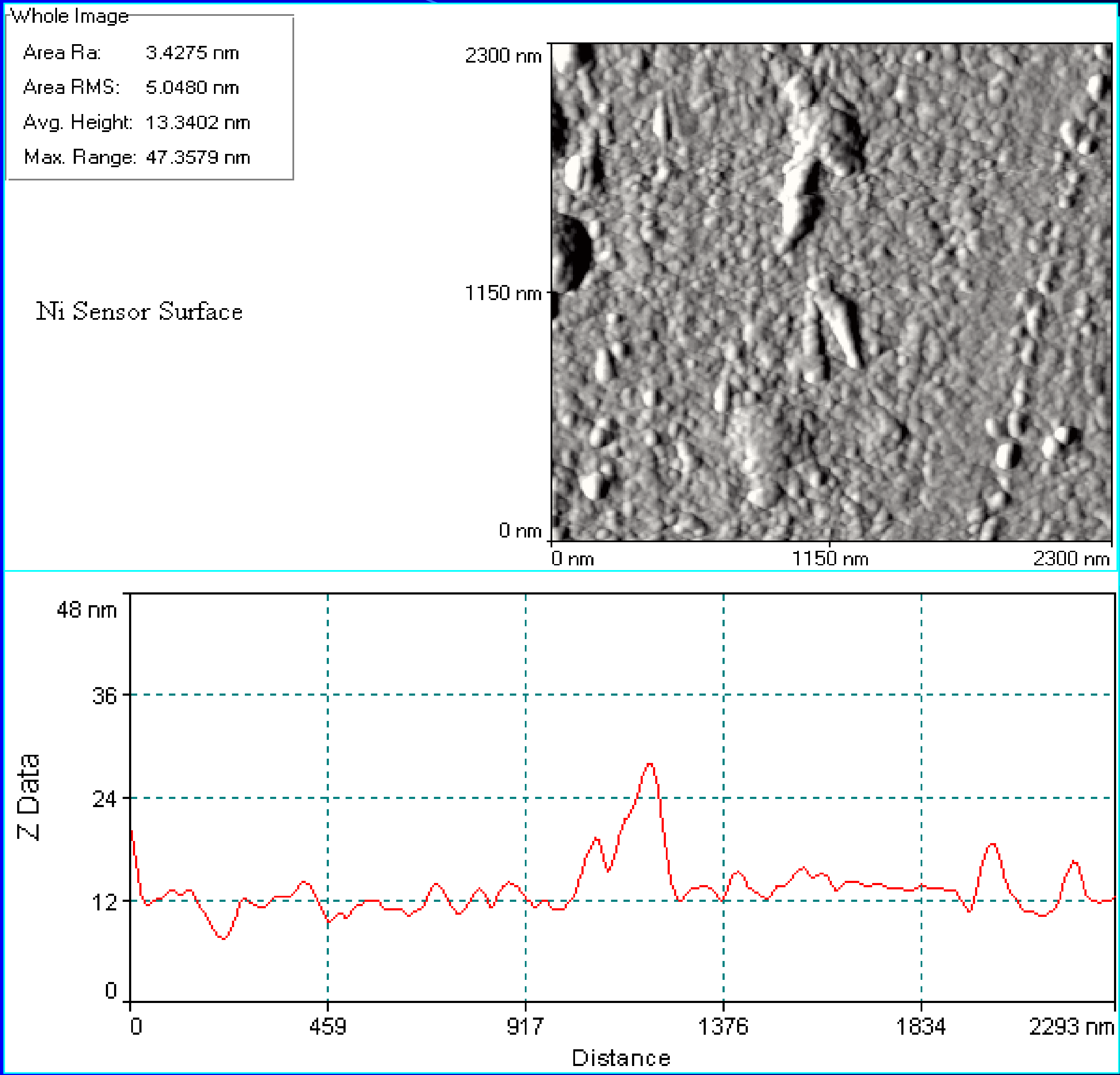
AFM Surface Roughness Measurements

- Atomic Force Microscopy (AFM) was utilised to determine surface finish on the Nickel sensor.
- Apparatus consists of an atomically sharp silicon tip (3 μm length) attatched to the underside of a reflective micro-cantilever.
- Micro-stylus is moved back and forth over the material surface , the cantilever deflection is determined by an interferometric technique.





AFM Surface Roughness Measurements



Conclusions

- Hot-film and hot wire measurements correlate in close proximity to the wall.
- The strength of the correlation in the near-wall region is verified by the similarity between the wavelet transforms of a film and nearby hot-wire
- AFM measurements of surface roughness for the hot-film sensor are of the order of 20 nm, 100 times greater than molecular size.