The Abdus Salam
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SMR 1829 - 28

Winter College on Fibre Optics, Fibre Lasers and Sensors

12 - 23 February 2007

Using inelastic (non-linear) phenomena in distributed fibre optic sensor systems

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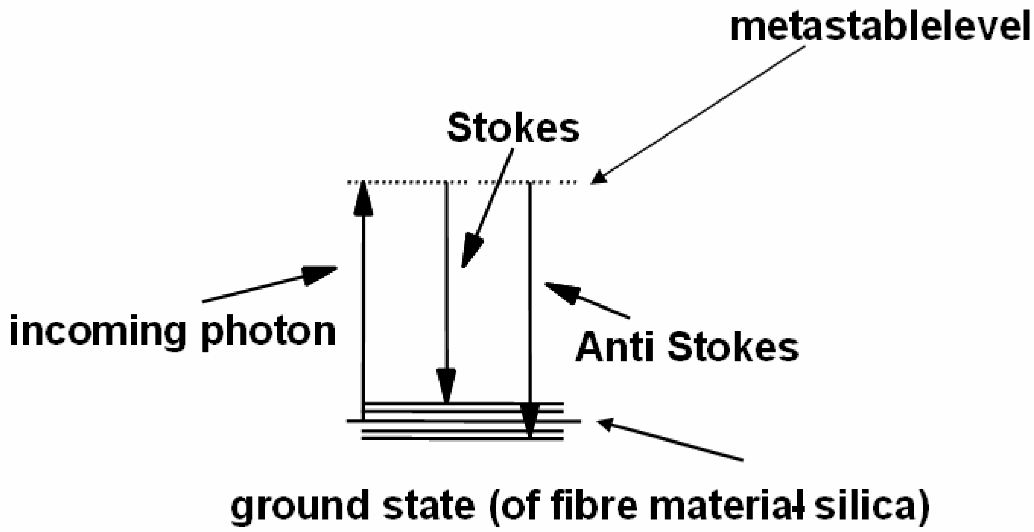
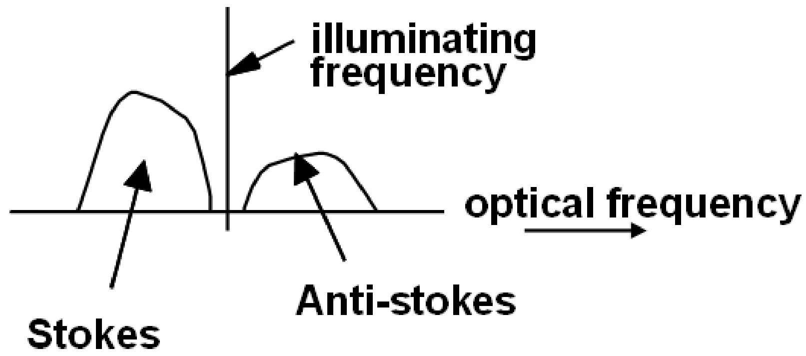
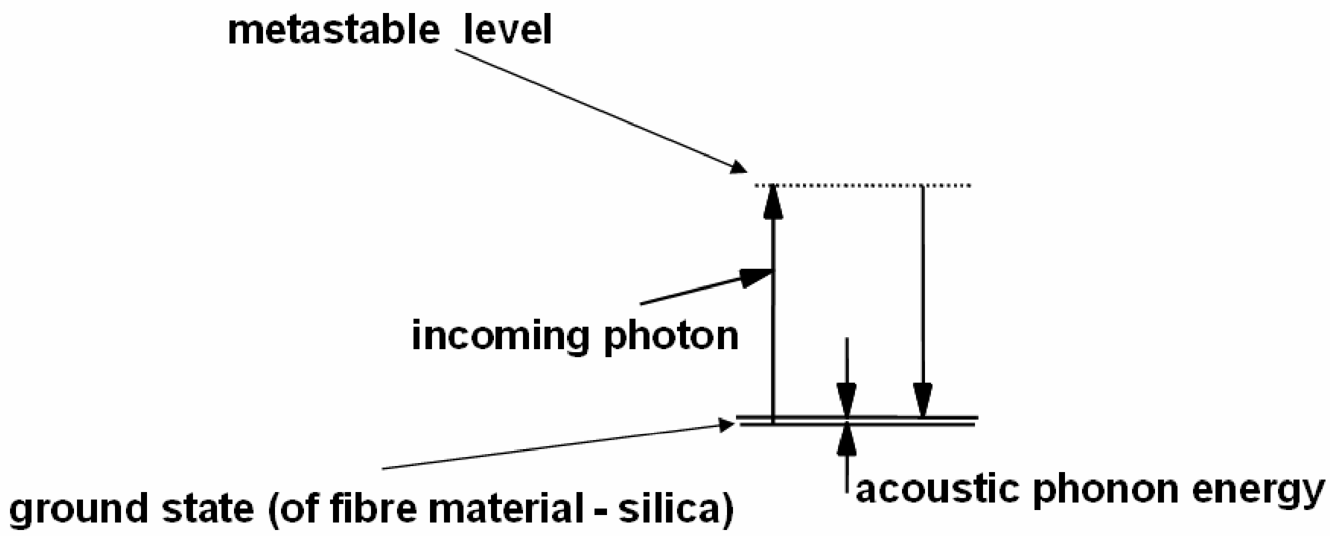
Non-linear effects for sensing – recapping the basics



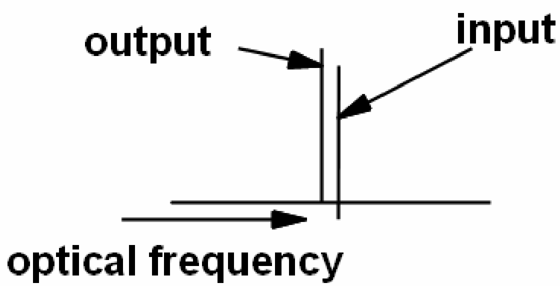


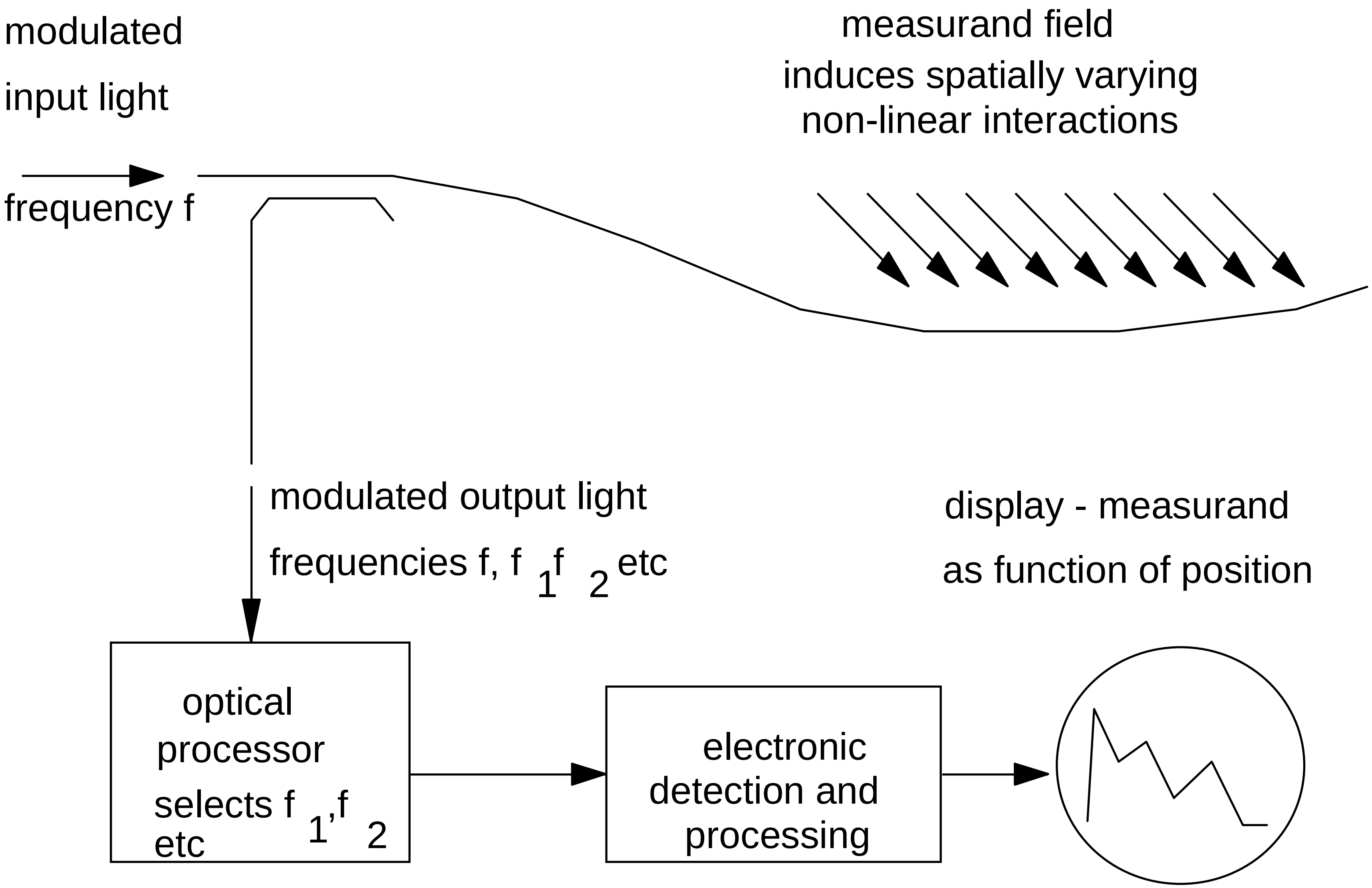
RAMAN: power ratio in Stokes and anti-Stokes f(T) alone equidistant from carrier

Non-linear effects for sensing – recapping the basics



<u>BRILLOUIN</u> *(stimulated)* –
Output frequency offset depends on $v_{acoustic}$ i.e. temperature and strain





Non linear optics for distributed sensing – general features

Starting with Raman Scatter

- An effect which occurs in all materials
- The Stokes and anti – Stokes frequencies are downshifted and up-shifted in frequency respectively

Raman spectrum and impulse response

- The Raman spectrum is a feature of the material and, in shape, is mirrored about the excitation wavelength (when plotted on a frequency axis)
- Relative populations at specific wavelength *for spontaneous Raman scatter* depend on Raman spectrum and temperature *(exp(qV/kT) class of relationship)*
- The impulse response is related to the frequency domain Raman spectrum via – as usual – the Fourier transform

The Raman impulse response of silica

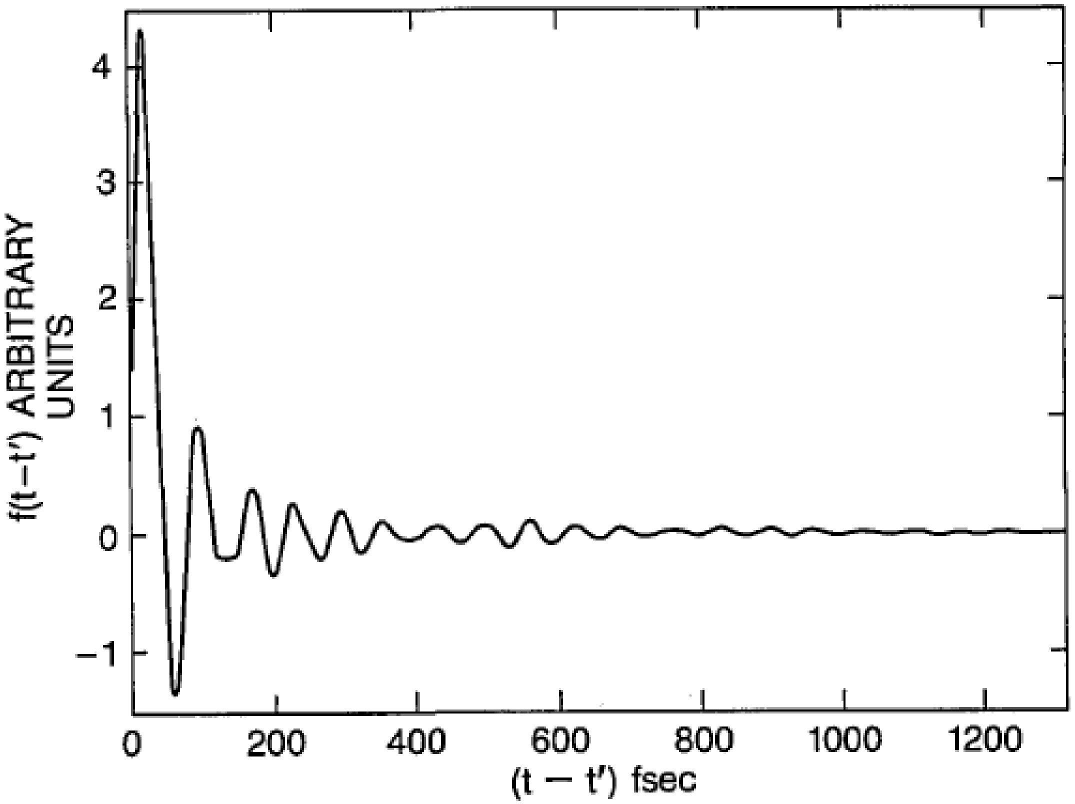
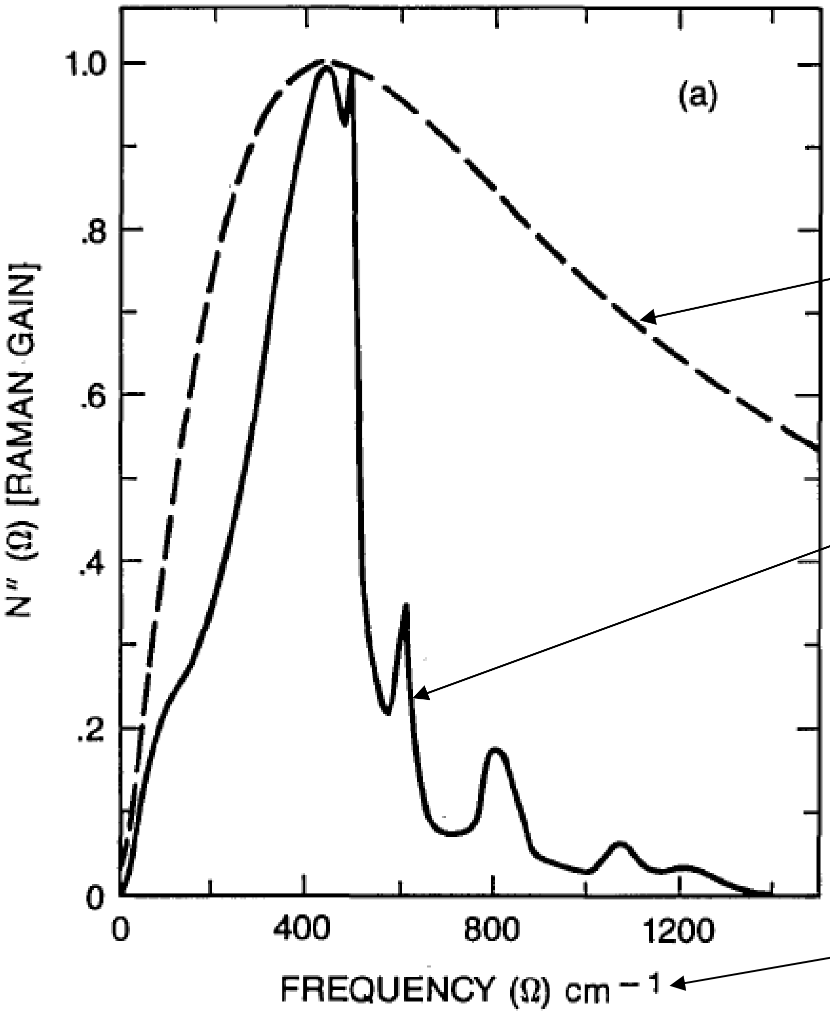


Fig. 2. The Raman time response function for silica-core fibers.

Best fit exponential transient – 76 fsec time constant

Roger Stolen at al - JOSA B, vol 6, June 1989, pp1159- 1166

Raman gain curves (*same reference*)



Inverse FT of 76fsec decay

Experimental values

Frequency in wave numbers offset from excitation frequency

Some insight into these numbers

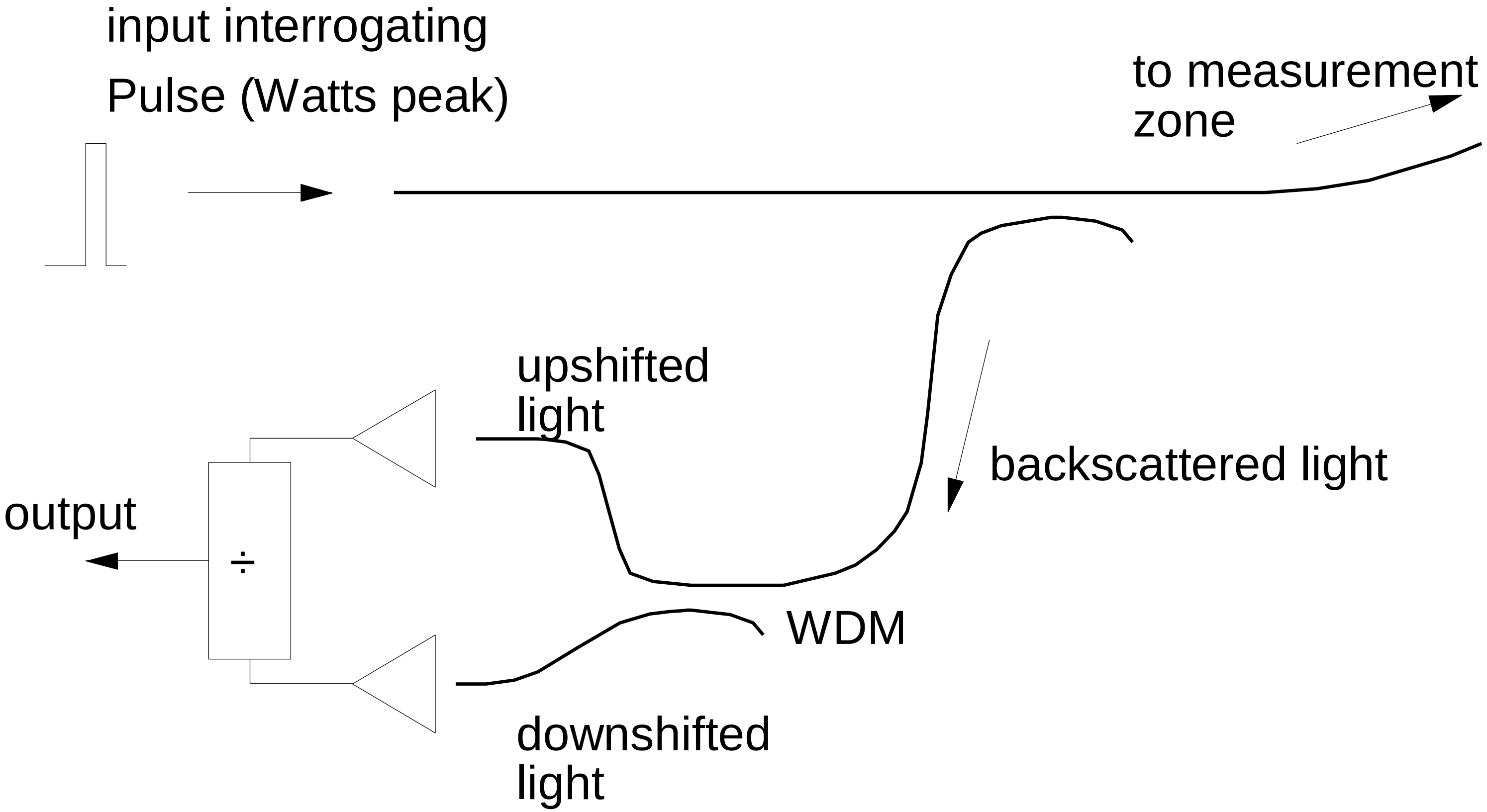
- 500 wave numbers is about 125nm wavelength difference at 1500nm
- *i.e about 8% differential*

- Stokes and anti Stokes are then about 250nm apart

- At room temperature the power ratio is about 3000!

More on the implications of the wavelength differential

Offset in wavenumbers	Approximate Offset in wavelength	Approximate Exp (qV/kT) value
500	125	3000
400	100	600
300	75	90
200	50	25



Raman distributed temperature probe : basic schematic

Designing the offset

- Find best offset wavelength considering:
  - Value of Raman gain
  - Ease of separation of and maintaining stability of spectral components
  - Ease of measuring and accurately inverting the exp (*qV/kT)* ratio to obtain temperature *(detection noise etc, practicalities of laser source among many relevant factors*

Another observation – Rayleigh scatter attenuation

- The Stokes and anti Stokes wavelengths are in the ratio ~ 1.08/0.92 depending on wavelength offset chosen
- Rayleigh scatter depends on $(1/\lambda)^4$
- This ratio is around 1.7 to 2 – need to apply attenuation correction too…

The result – Raman DTS is offered by many vendors in many countries

- In the UK – Sensa (Schumblerger) derive from the early work on Raman at Southampton University – an example from their web site -

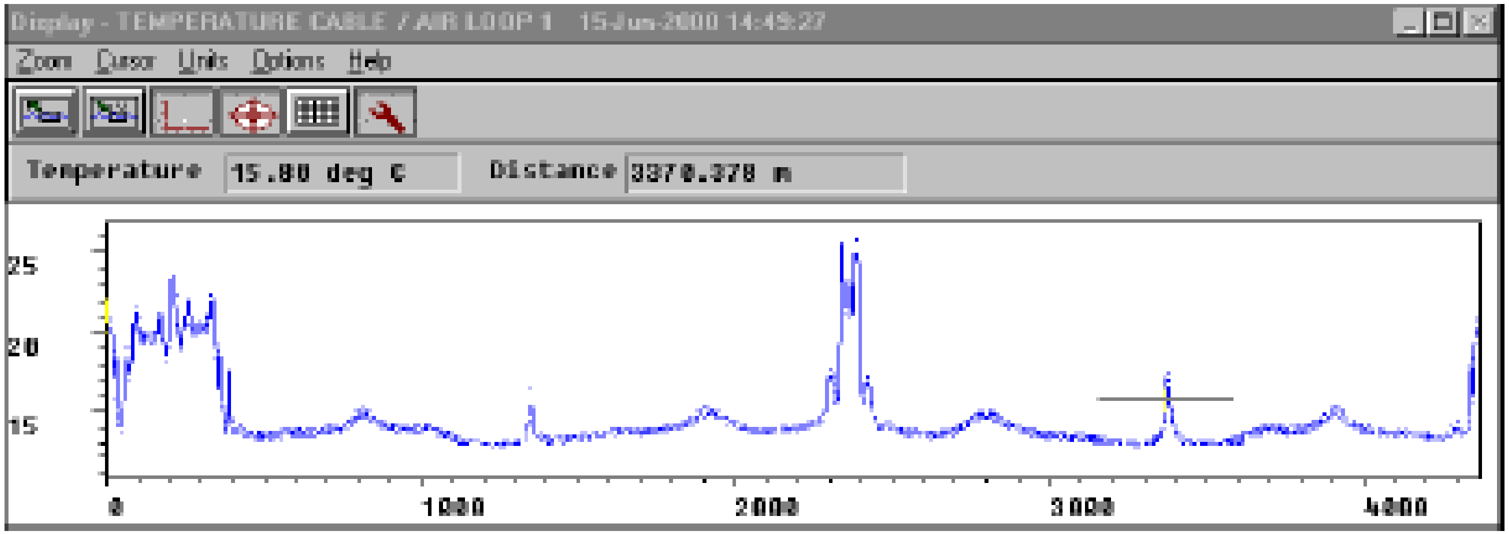


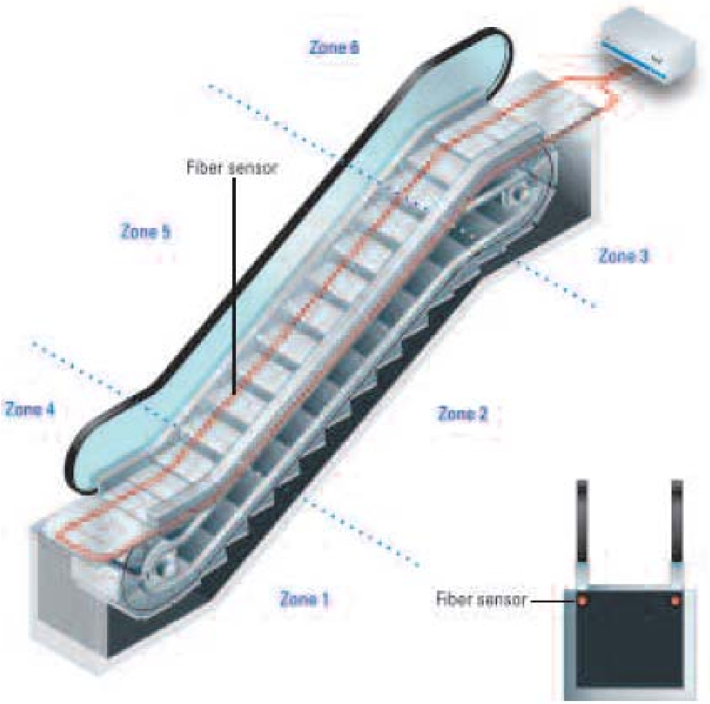
Figure 3 - DTS Temperature Profile Example

Application sectors

- Fire in tunnels *(Sensa)*:

Escalator installations

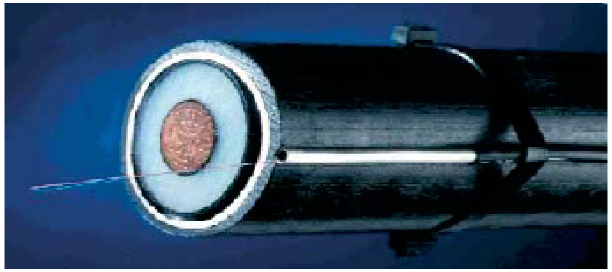
Escalators often form an integral part of the communication routes in buildings. It is, therefore, important that fire detection measures extend to the escalators themselves. Escalator fires can be caused by faulty electrical equipment or roller bearings, or hot works igniting accumulated dust and discarded materials inside the escalator. Sensa's Dual Integrity systems are easy to install on escalators and provide reliable fire detection and continuous condition monitoring.



A typical layout for the fiber optic heat detection cable with system zoning information. In this example, the system is programmed with multiple detection zones along the length of the escalator. Areas at either end of the escalator are typically higher risk, as they are often sites for electrical equipment and are most prone to collecting discarded materials.

Application sectors

- Power line monitoring *(Sensa)*



ATTACHED OPTICAL FIBER

Advantages
- Easier to install
- Fewer joints
- Lower fiber losses

Disadvantages
- Further from the conductor
- Not suitable for pulling through ducts

INTEGRATED OPTICAL FIBER

Advantages
- Closer to the conductor
- Suitable for pulling through duct

Disadvantages
- Higher number of joints
- Greater fiber losses
- Specialised jointing

Application sectors

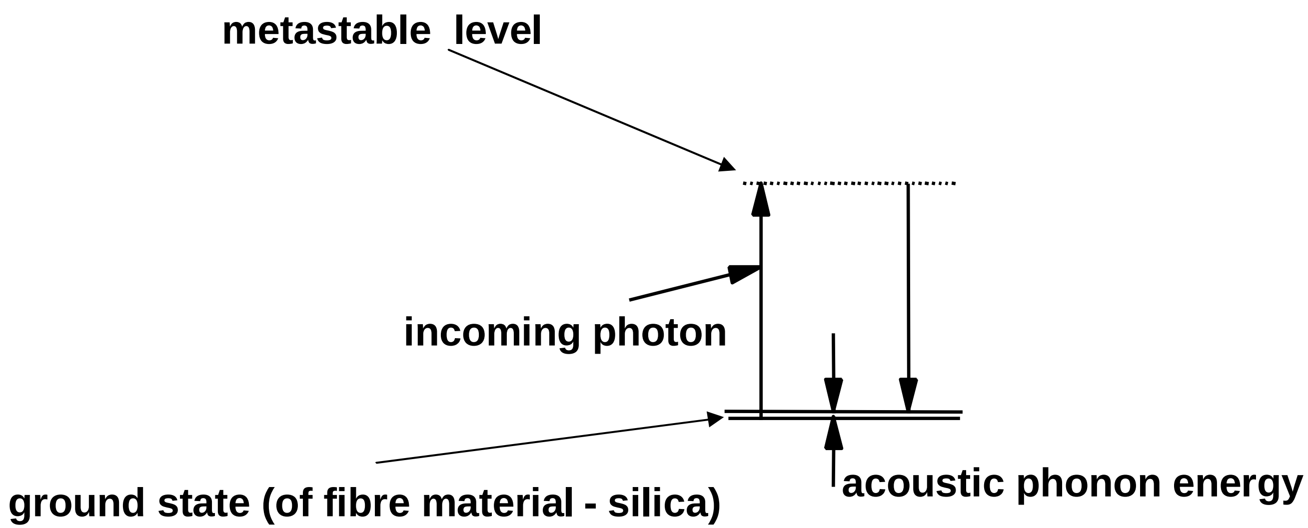
- Others include
  - Oil and gas, production, exploration and recovery
  - Some process control systems

and many others….

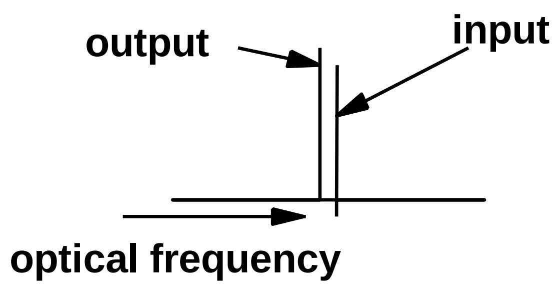
The Raman DTS

- Competitive distributed temperature system
- Resolutions of the order 1 metre, 1^{o}C, depending on ranges and integration times
- Many real and demanding applications have been identified and exploited
- Principal benefits – very simple installation and interface and OTDR cost reasonable
- Available as product from several vendors

And now to Brillouin Scatter: first a reminder…



<u>BRILLOUIN</u> *(stimulated)* – Output frequency offset depends on $v_{acoustic}$ i.e. temperature and strain



Now to Brillouin scatter - basics

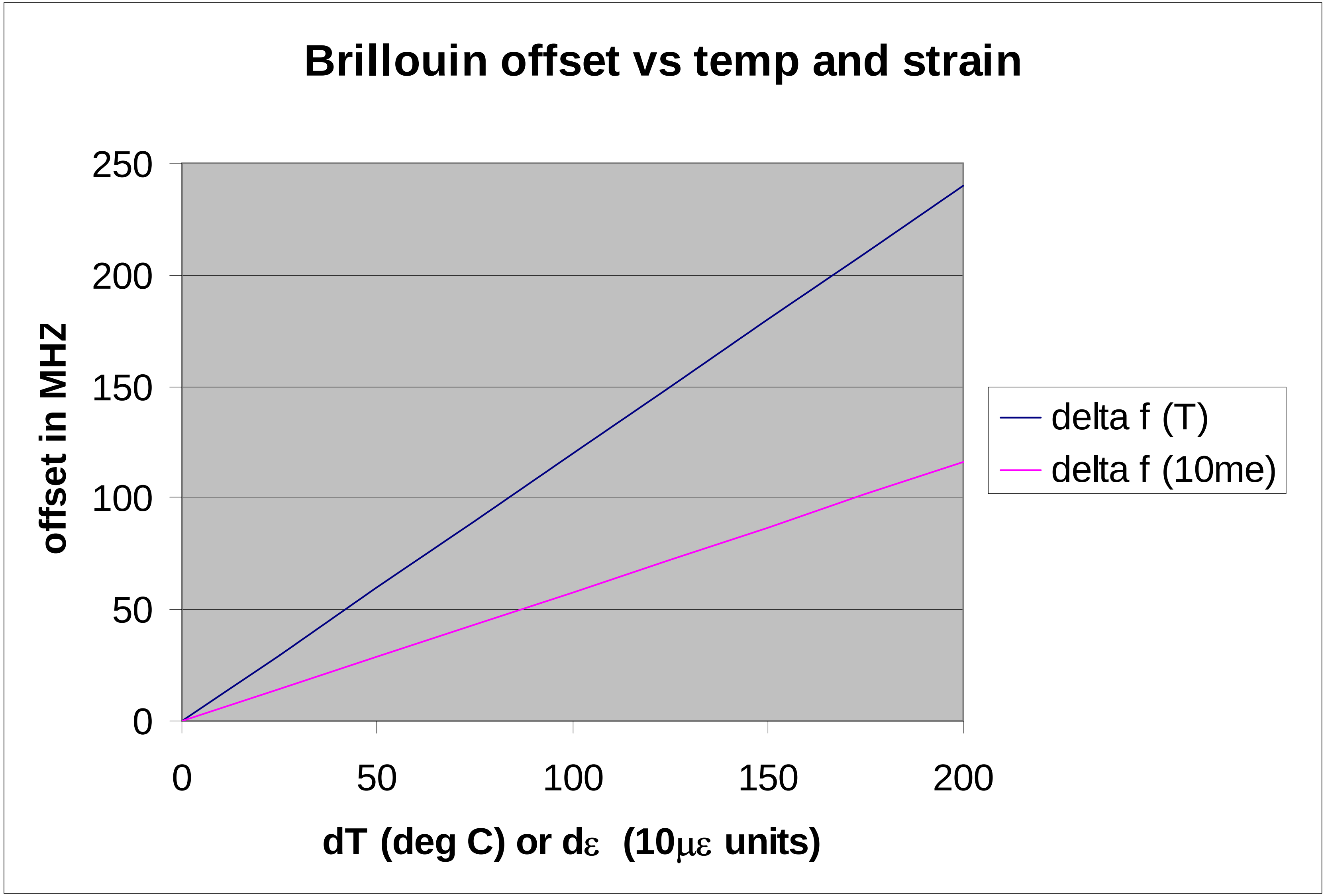
Stimulated Brillouin Scatter:

measures acoustic velocity via optical wavelength (assumed known and fixed)

$$\Delta v_{ac} = K_{\varepsilon} . \varepsilon + K_{T} . \Delta T$$

$$\Delta f_{SBS} = \Delta v_{ac} / \lambda_{light}$$

Δf_{SBS} ~ 1.2MHz/K and 58kHz/$\mu\varepsilon$ at $\lambda_{light} = 1.3\mu m$.
from a starting frequency of ~ 13GHz


Brillouin offset vs temp and strain
250
200
150
100
50
0
offset in MHZ
0
50
100
150
200
dT (deg C) or dε (10με units)
delta f (T)
delta f (10me)

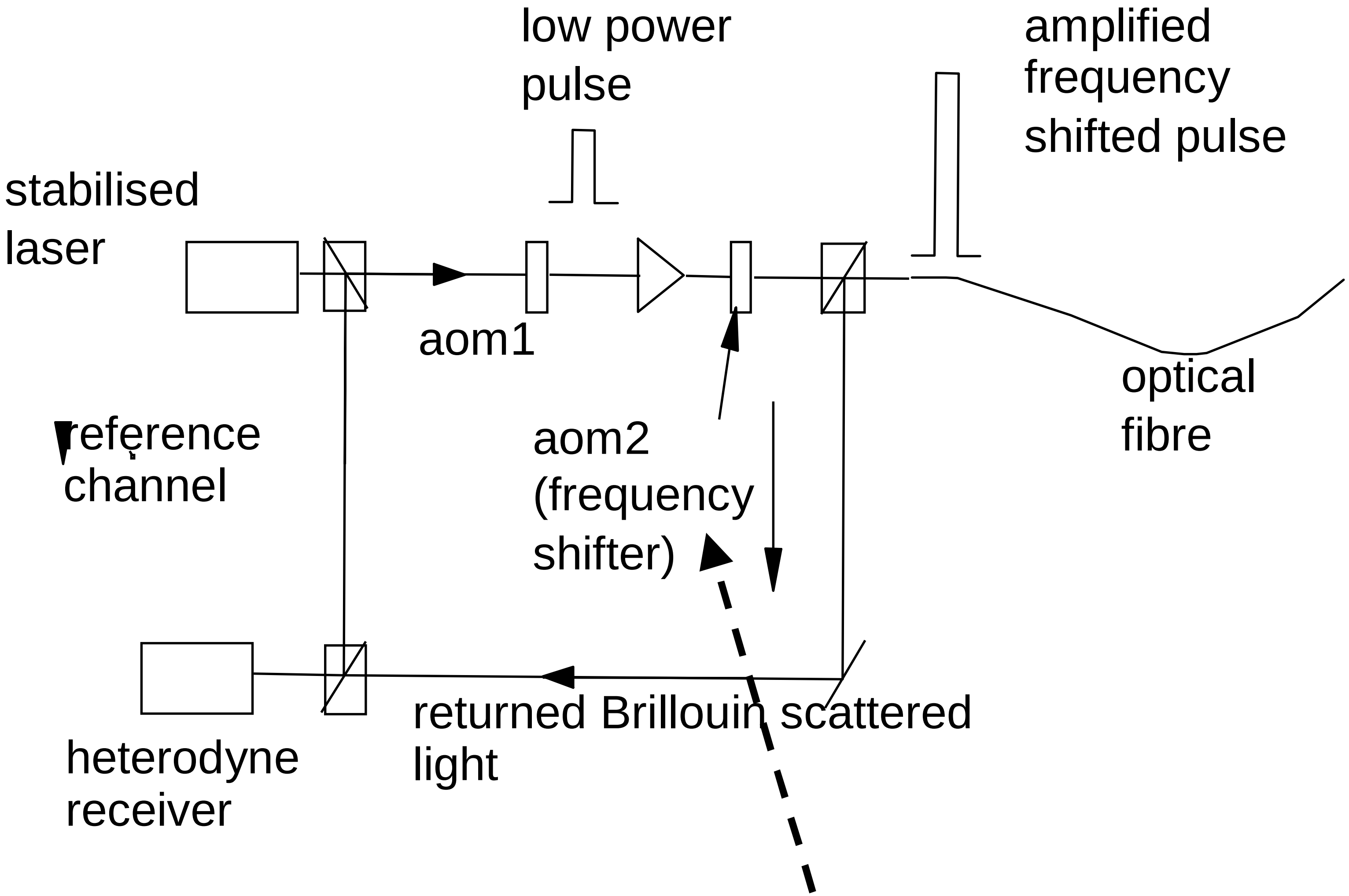
Applications and commercial instruments

- First applied as a long range cable monitor especially for fibre communication cables in unstable areas

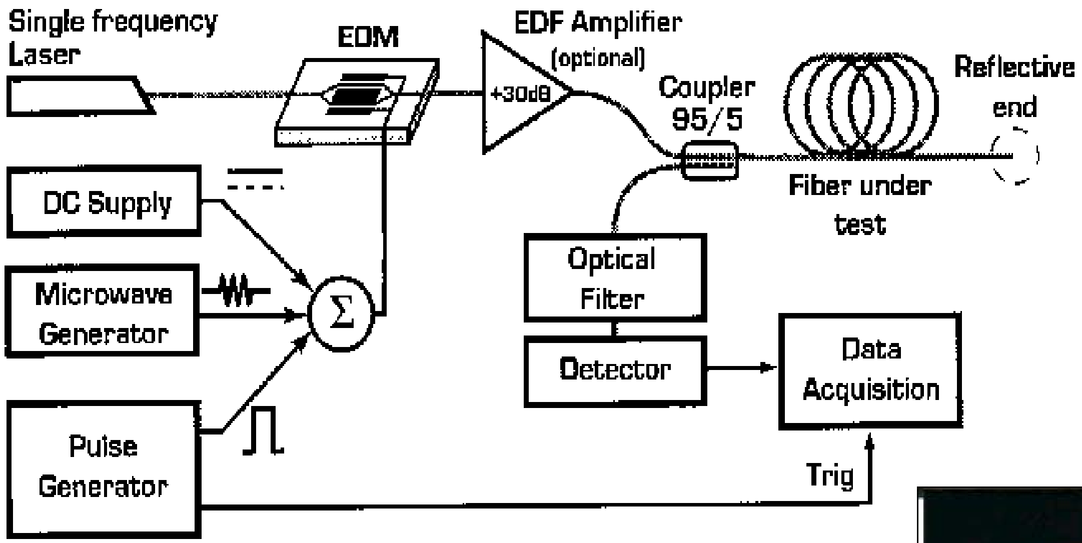
- Range to 100km, resolution to 1 to 10 metres, to 10 or less $\mu\varepsilon$ depending on integration times and settings

- Temperature crosstalk – $1^{o}C$ temperature change gives about equivalent to 20 $\mu\varepsilon$ *(for many applications this is not a problem…)*

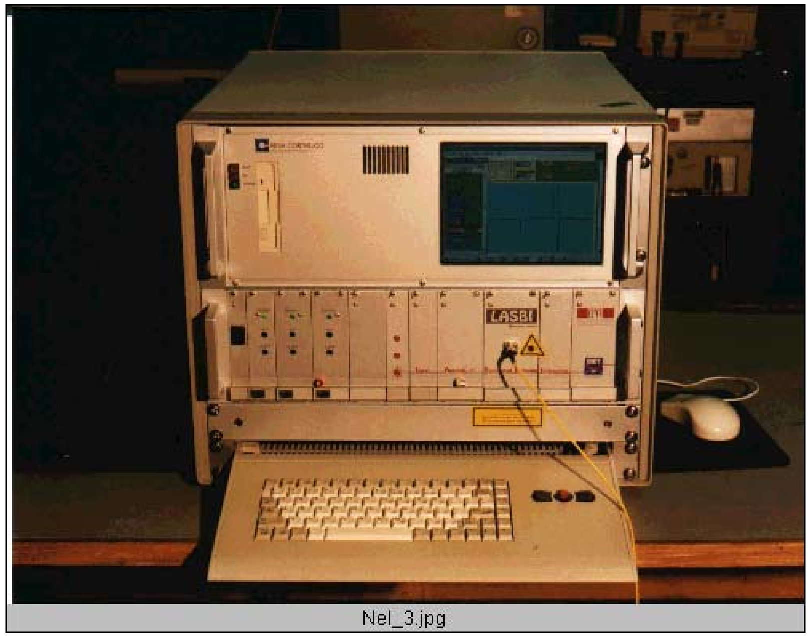
Many variations on Brillouin OTDR - BOTDR

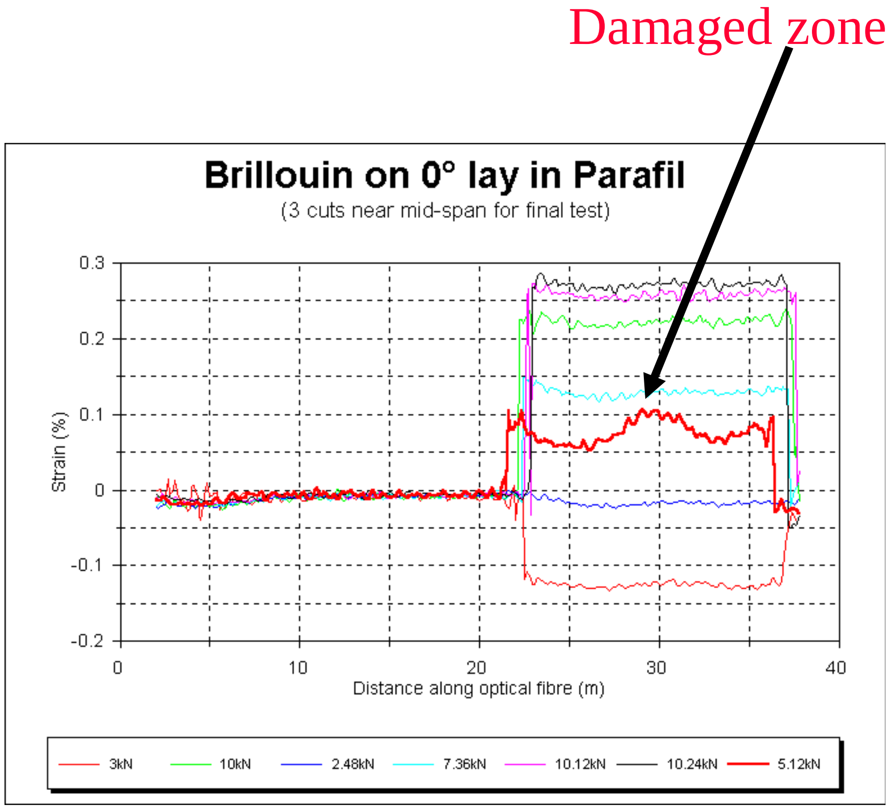


Scan frequency shift across Brillouin spectrum



Schematic diagram of a
Brillouin backscatter optical time
domain reflectometer, with a photograph
of a prototype instrument



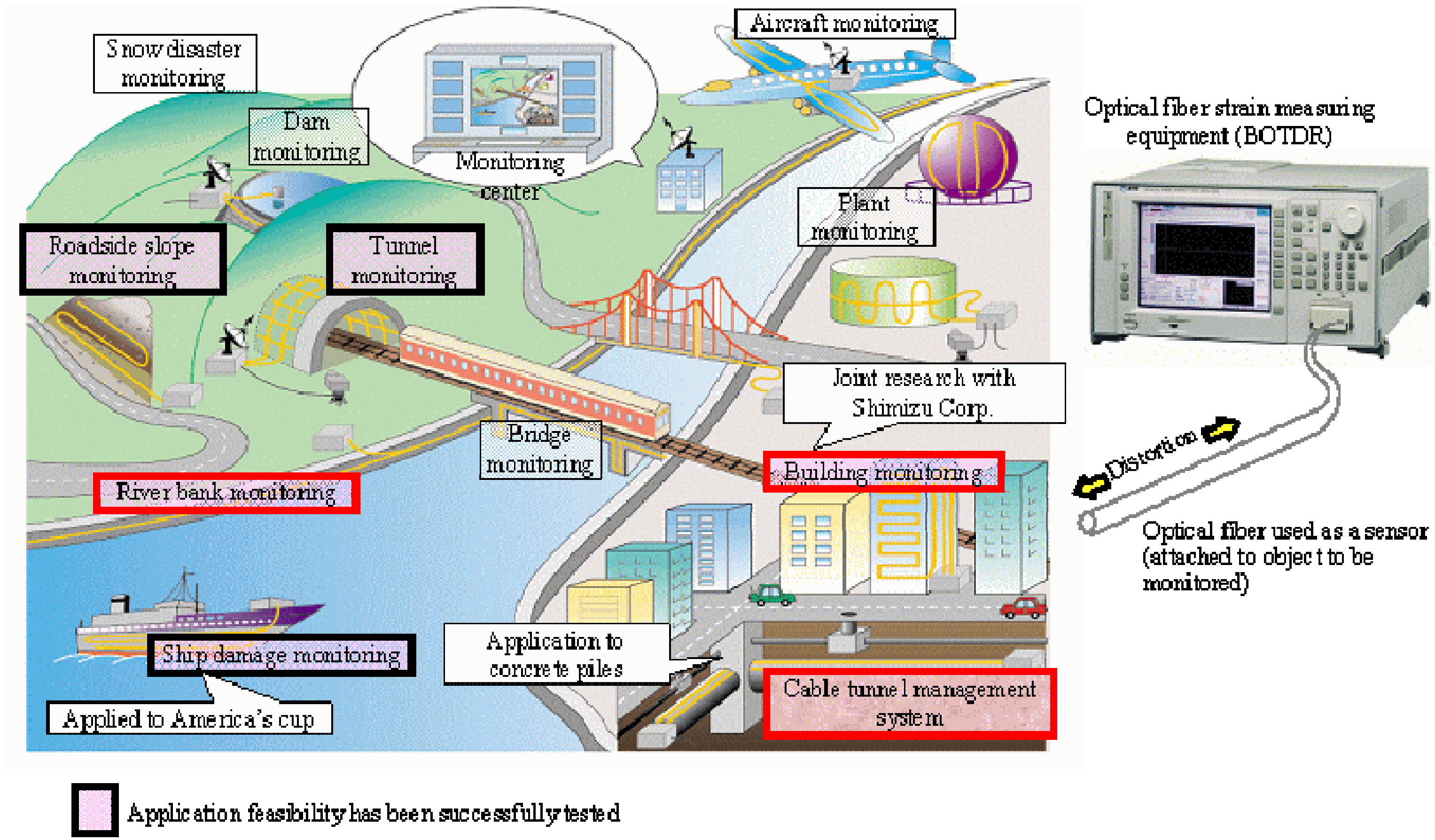


Measuring strength deterioration in marine ropes using Brillouin OTDR

Applications and commercial instruments

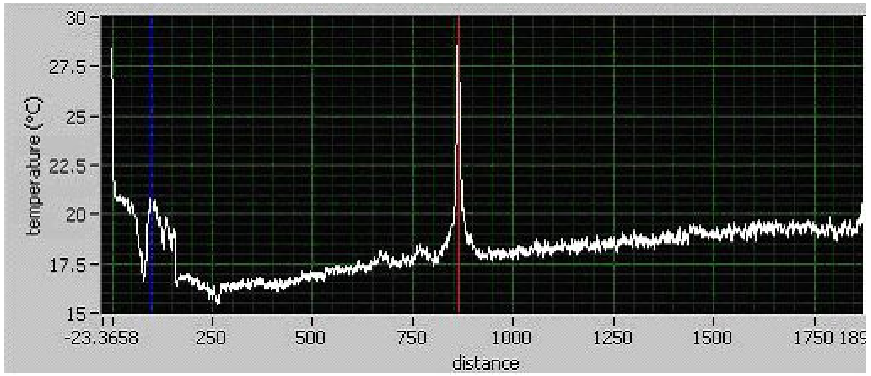
- From the NTT web site….

Main applications of fiber-optic strain-monitoring technology



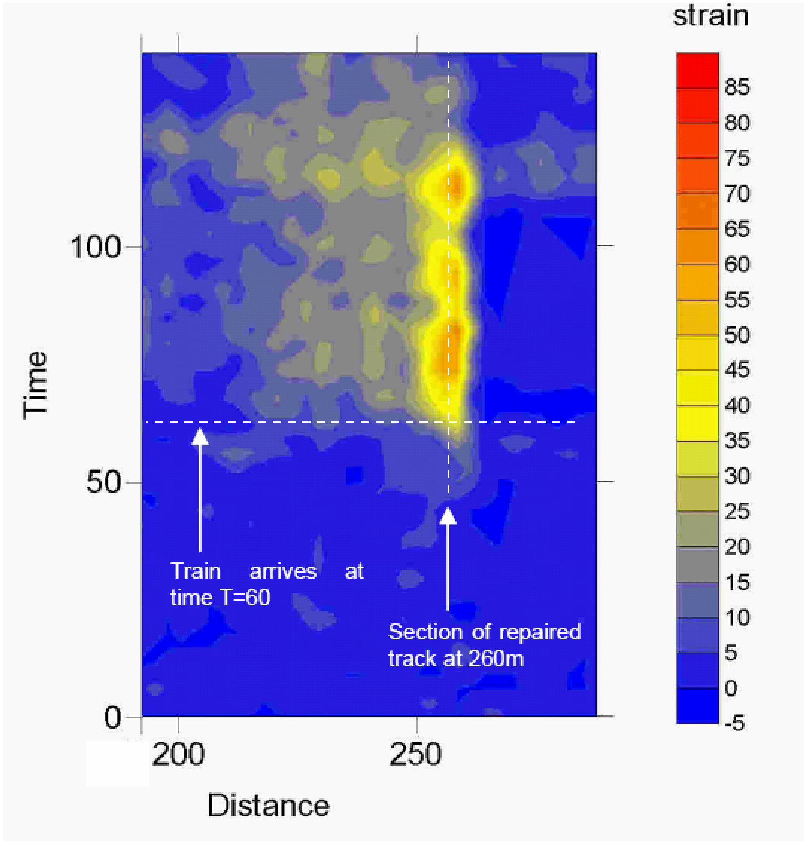
Others instrument manufacturers include…

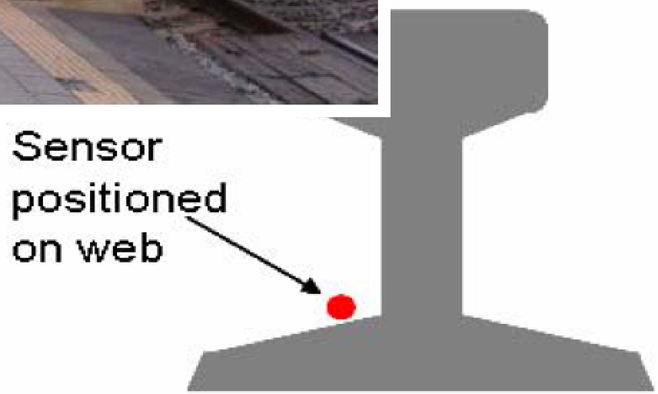
- Omnisens – Switzerland
- Sensornet - UK



Fire detection using distributed (Brillouin scatter) sensing *(Sensornet, UK)*

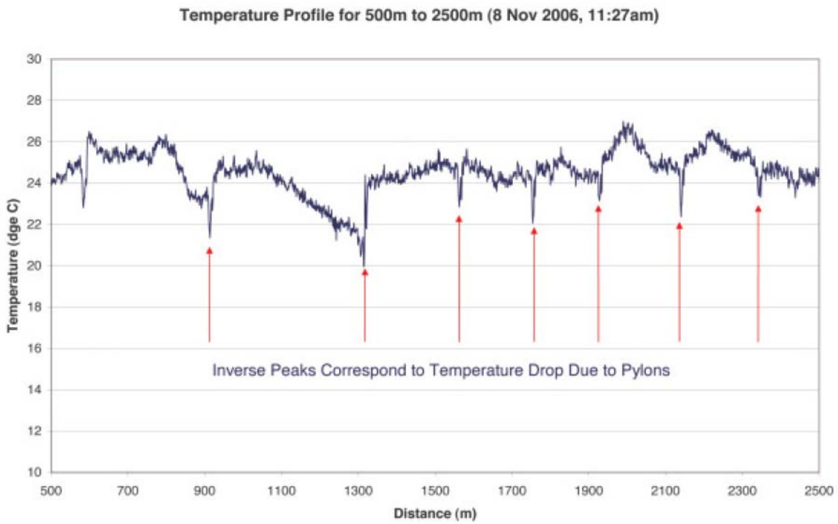
A trial system – railways

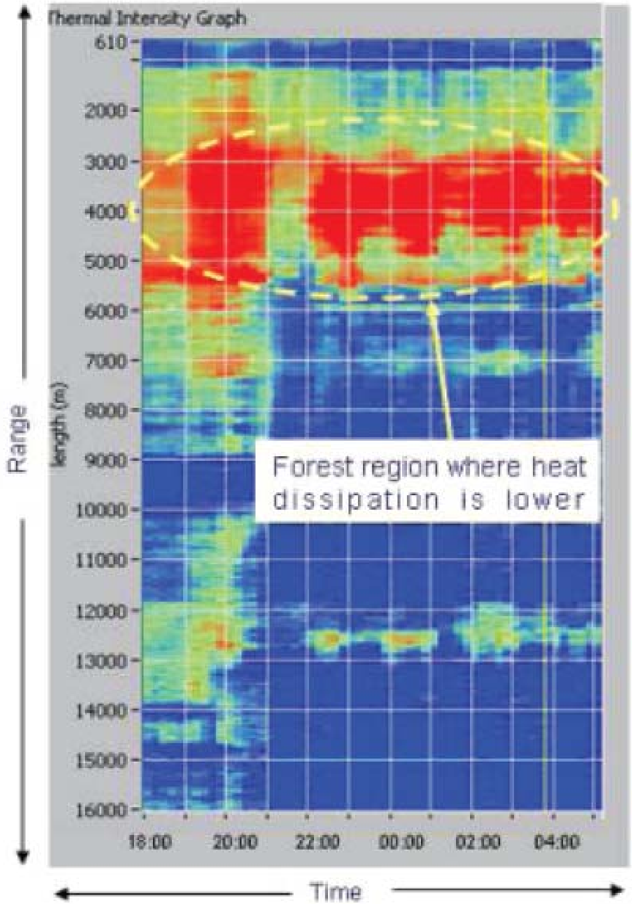




Sensornet UK

And to Brillouin in Power cables *(again Sensornet)*





Some comments on BOTDR

- The instrument is currently expensive… Inherently the system is complex and requires precision engineering

- Cost undoubtedly limits application

- And the strain transfer interface requires careful engineering – microbends and excess losses

More comments on BOTDR

- There have been many demonstration systems and
- much research on Brillouin continues (e.g as a means to slow light!)
- For temperature the competition is Raman
- Still to mature into a routine product – except BOTDR as test instrument for fibre communication cables – *very specialised.*

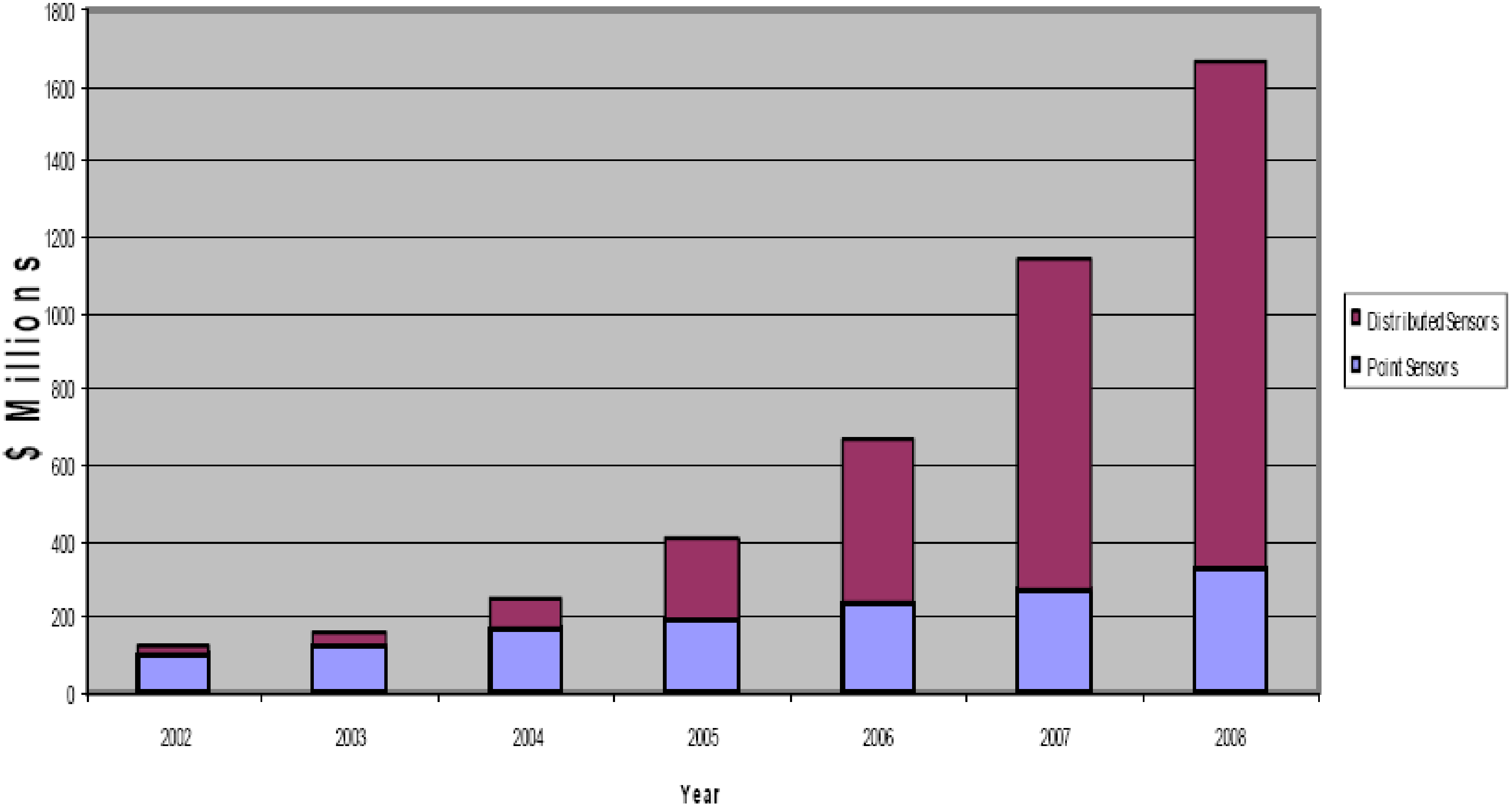
Now to some reflections on markets and application

- Distributed sensing is alien to users

- BUT distributed sensing does offer unique benefits in acquisition and installation of sensor arrays

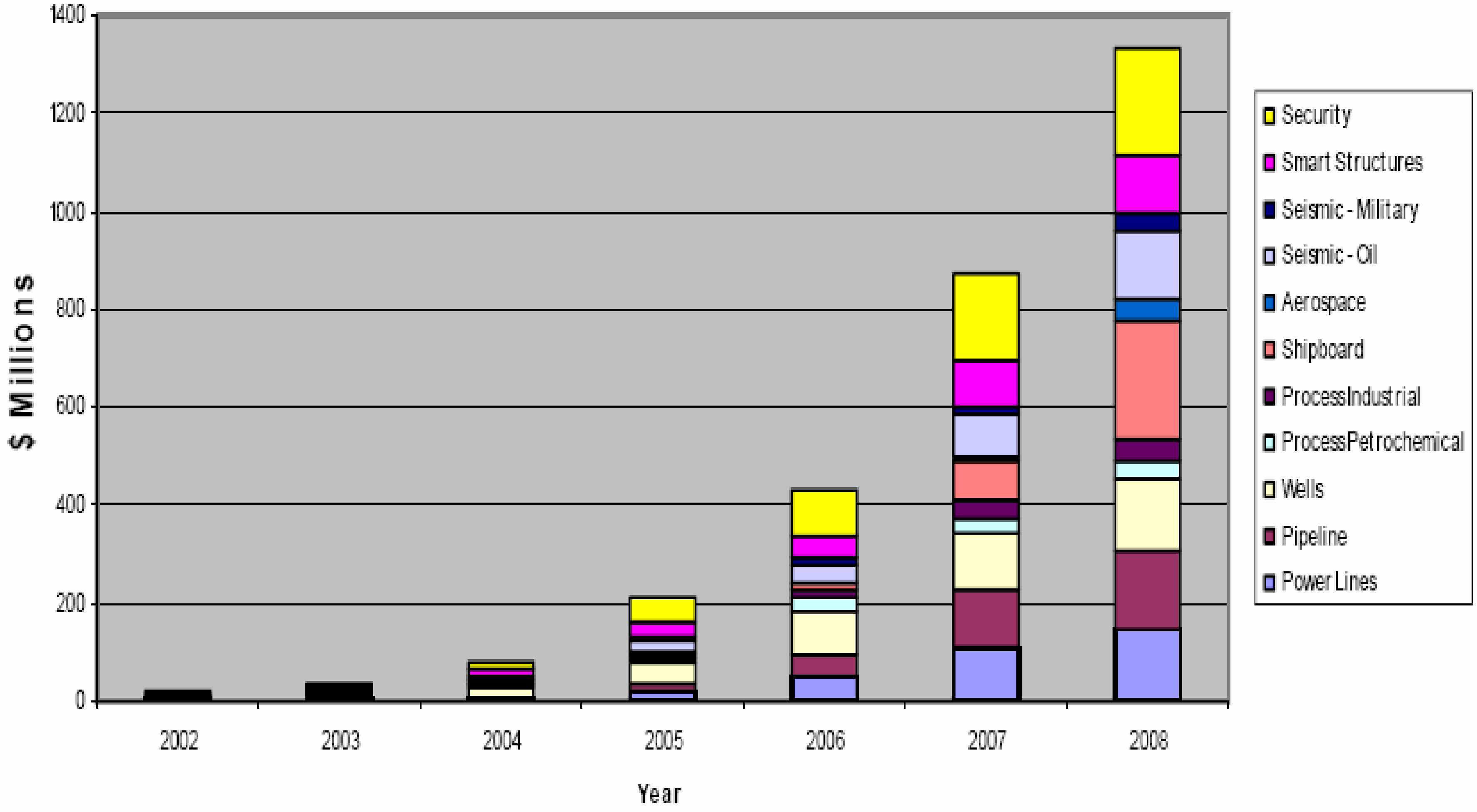
- Distributed sensing is unique to fibre optic sensor systems… *and hence the first comment above!*

What of the future???
Market prospects – the drift to distributed…



Dave Krohn, 2004, SPIE 5589 -06)

And within the distributed envelope…



Comments on distributed sensing…

- Linear systems (Rayleigh, reflections) simple to implement but measurements best suited for alarms, and often need special fibre and / or cable to interface to the measurand

- Non linear interactions – Raman and Brillouin most successful so far, and often based on normal fibres

- Temperature system – the DTS is the only established product

- Strain based interactions over long distances….microbends!! And excess losses

More comments on Distributed Sensing…

- Many applications – we’ve seen samples
- Fire / heat detection is real for tunnels etc
- Some installations on leak / strain / thermal fields detection on pipelines, boreholes etc. especially oil related
- Prospects for intruder, vibration etc based on phase sensitive systems

- Market optimism… ample opportunity…