POLITECNICO DI TORINO

Department of Environment, Land and Infrastructure Engineering

Master of Science in Petroleum Engineering

Critical Analysis and Applications of Optical Fiber Sensors in Oil and Gas Industry

Supervisor:

Prof. Alberto Godio

Candidate:

Arsalan Ahmed
229155

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Abstract

This thesis is about the applications and critical analysis of the optical fiber sensors specially FBGs, DTS and DAS for downhole monitoring and Geophysical measurement.

As the petroleum industry is growing very fast, for increasing profits and yield it demands the involvement of new technology for cheaper production, well and reservoir management. In this thesis the new technology of measuring important parameters like pressure, temperature and strain are discussed with its criticality and application. Among them Fiber Bragg Gratings (FBGs) are in practice for numerous measurement of different parameters like temperature, strain and pressure and its application in oil and gas is also very effective and are capable of measuring under harsh environment. Moreover, the critical analysis shows that it is sensitive over the wide range of vibrational frequency from 5Hz to 2.5kHz of range, these frequencies preserve the mandatory information of subsurface geological structures. With the integration of mechanical transducer into FBGs, results in enhancement of amplitude and frequency of a sensor. likewise, for resisting high temperature and pressure of downhole which is approx. 175 Degree Celsius and 40Mpa pressure respectively, different packaging and femtosecond laser side-illumination were used by different researchers for withstanding maximum temperature till 1100 Degree Celsius. And the case study shows the successful application of FBG in well logging.

moreover, the other case study for DTS performance analysis in CO_2 injection wells at U.S coast gulf to monitor the leakages of CO_2. The application shows the measurement of temperature variation along the length of the injection well was about 2 to 15 minutes and the analysis also show the temperature deviation at higher depth due to instrumental drift.

The third portion is on the application and analysis of the Distributed Acoustic Sensing (DAS) here it is known that it is low cost effective and with no production delay novel technique. With repeatability and coverage for seismic data acquisition in VSP, for micro-seismic investigation, Hydraulic Fracture monitoring and reservoir and well surveillance. Here it is discussed its application and analysis on limitation that occurs during its application in upstream and with geophysical measurement.

Lastly, more comprehensive sensitivity analysis in future is recommended to minimize instrumental drift and sharp warming at high depth

DEDICATION

To My Family

ACKNOWLEDGEMENTS

Thanks to HEC for giving me an opportunity to study in a European university, to my Supervisor Prof, Alberto Godio and to my family for too much support

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Chapter # 1

Introduction

Optical fiber is very appealing and attractive technology in monitoring temperature, pressure and strain of specific portion or along the length of the fiber. Over the conventional permanent downhole sensors, the main advantages are great immunity to electromagnetic interference, resistance to high temperature, greater sensitivity, ease of integration into large scale fiber network and communication system and capability of multiplexing. [1,2,3]. The development of the optical fiber technology was introduced years before [4] [5]. And with the passage of time new products related to the sensing were developed for example: temperature sensors, chemical and accelerometers probes, optical fiber gyroscope. Its application ranges from many fields like in

- Civil Engineering
- Industrial Application
- Military hardware
- Chemical sensing
- Security system monitoring etc.

The fiber optics technology is now allowing new possibilities for sensing variety of parameters for example. pressure, temperature, strain, vibration and flow behaviors, reservoir surveillance and downhole monitoring. For its uses in upstream specially in downhole monitoring the optical fiber included are,

- Fiber Bragg Grating Sensors (FBGs) [7]
- Distributed Temperature Sensors (DTS) [6]
- Distributed Acoustic Sensors (DAS) etc.

The fiber sensors which are specific for downhole monitoring in petroleum industry are always targeted by extreme environmental conditions which are always hostile in nature. Reservoir surveillance with accuracy and reliable information is mandatory for oil and gas production rates and yield. Till now, the petroleum industry is highly dependent on retrievable wireline sensors which run into the hole for measuring important parameters such monitoring gives the picture of the reservoir and borehole for analysis and the process repeated regularly with period. Continuous real time data can be obtained if the sensors installed downhole permanently, But the main concern regarding the transducer technology is of its reliability for long period of time in harsh environment this is the main bottle neck related to the permanent monitoring benefits.

Chapter # 2

Working Principles

Basics of Technology

Optical Fiber Sensors

These are Sensors uses fiber optics for sensing as an (intrinsic Sensors) and relaying of signal from remote sensors to electronics as an (extrinsic Sensors). The main foremost properties which make fiber optical sensors unique from electronic gauges are of their immunity from electromagnetic interference, bad conductors and withstanding properties at high temperature environment.

Intrinsic Sensor

Primarily, it can be used to measure temperature, pressure and strain and secondly, other parameters like intensity, phase, wavelength and polarization can be measured by customizing the fiber optics. fundamental benefit of optical fiber as an Intrinsic sensor is the distributive sensing ability over a long distance. [8]

Parameter like temperature can be measured by considering Rayleigh scattering, Raman scattering or the brillouin scattering in fiber optics. Optical fiber sensors are also in use of finding direction as well by using Long-Period fiber grating (LPG) fibers. [9]. In oil and Gas industry optical fiber sensors uses as Hydrophone for seismic application. [10] for downhole measurement like temperature and pressure (distributed Temperature Sensing) [11][12]

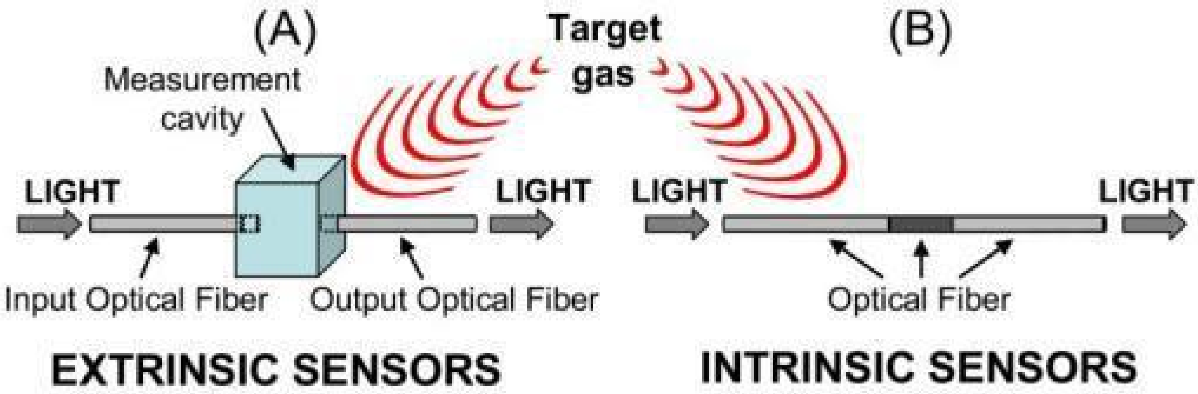


Figure 1. Difference between Extrinsic and Intrinsic Sensors

Extrinsic Sensor

To transmit modulated light from electronic gauges to fiber optical transmitter the extrinsic fiber optic sensors are in common practice which uses fiber optical cable. The major application of the extrinsic fiber optics is in aircraft jet engines for transmitting the radiation to the pyrometer and moreover they are used to measure vibration, rotation, displacement, velocity, acceleration, torque and displacement. [13]

2.1 Working Principle of Fiber Optic Sensor

The working principle of fiber optic sensor is Total Internal Reflection.

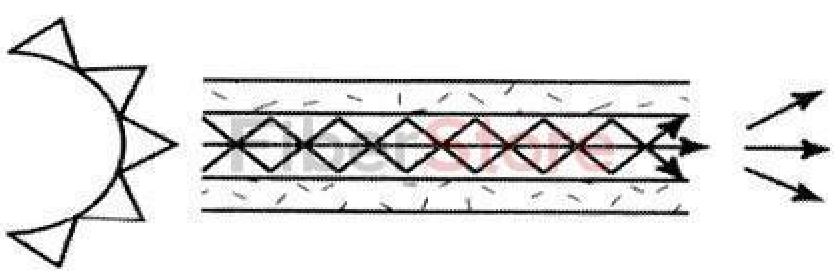


Figure: 2 Total Internal Refraction

When light travels from the medium of lower refractive index to higher refractive index, it bends toward the normal. The incident ray made an angle to the perpendicular called the angle of incidence and where the angle made by the refracted ray at the point of incidence in the other medium called angle of refraction.

2.2 Fiber Bragg Gratings

The most important device in sensing and fiber communication fields. As to mention its importance it is prominent in the field of health to the aerospace and are more widely in dams, bridges, high buildings and other important structures, in mining industry. Following are the advantages of FBGs.

1. Low cost
2. Easy fabrication
3. Anti-interference
4. Small

It is an optical fiber sensor that refractive index changes periodically in the core zone along the longitudinal axis which form the grating. In the fiber the behavior of the rays is determine by the grating. It can be classified or divided in to two types based on different coupling models.

- Short Fiber Brag Gratings
- Long Fiber Brag Gratings

And based on the grating period:

- Uniform Fiber Brag Grating
- Non-Uniform Fiber Brag Grating

Short and long FBGs are included in Uniform Fiber Brag Grating. The scheme of the Fiber Brag Grating can be seen in Figure [3].

22.1 Fiber Brag Gratings Classification

Based on the variation in refractive index. Fiber Bragg Grating can be classified into several types some of them are discussed here.

- ### Uniform Fiber Bragg Grating

The most common fiber Brag Grating is the uniform FBGs. The refractive index modulation coefficient (v) and Period (Λ) are both constant. The core's refraction index distribution function in the fiber is given by this equation (i).

$$\Delta n(z) = \Delta n_o[1 + v\cos(2\pi z/\Lambda)] \qquad \text{i}$$

In the formula,

Δn_o =The average changing value of the refraction index

v =The modulation coefficient of refraction index (0<v<1)

Λ =the period of grating

Z = the position along the fiber axis direction

In Figure (3) the distribution function can be seen.

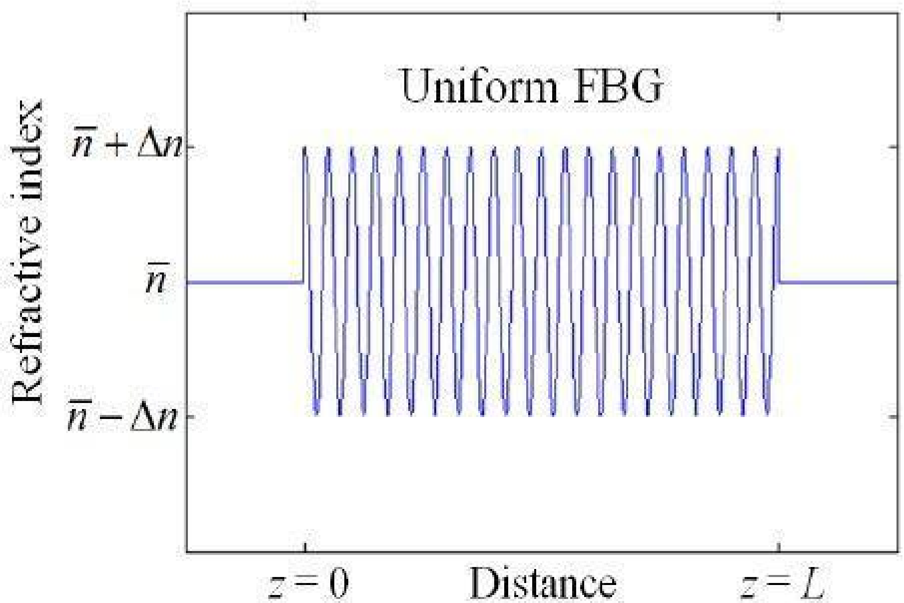


Figure:3 Uniform FBGs

The Fiber Brag Grating for reflection type is an excellent filter, with large reflection bandwidth, and by the light intensity the reflection rate can be controlled when the fiber is disposed by the ray. The application of this fiber is more common in the field of communication, fiber sensors and oil and gas industry as well.

- **Chirped Fiber Grating**

In chirped Fiber Grating the refraction index modulation coefficient is constant, and the grating period is variable along the axis direction of the fiber Figure (4). The linear chirped fiber is the common example of the chirped fiber. The refraction index variance can be showed in equation (2).

$$\Delta n(z)= \Delta n_o[1+v\cos(2\pi z/\Lambda_o+\theta(z))] \qquad \text{ii}$$

In formula.

Λ_o = The period in the center grating

$\theta(z)$ = The phase shift introduced by the changing of grating period

Different period is associated with different wavelength and the bandwidth in linear chirped fiber grating is very wide. Moreover, the dispersion is also very stable. Due to this chirped fiber grating is used to compensate the dispersion in Wavelength Division Multiplexer (WDM).

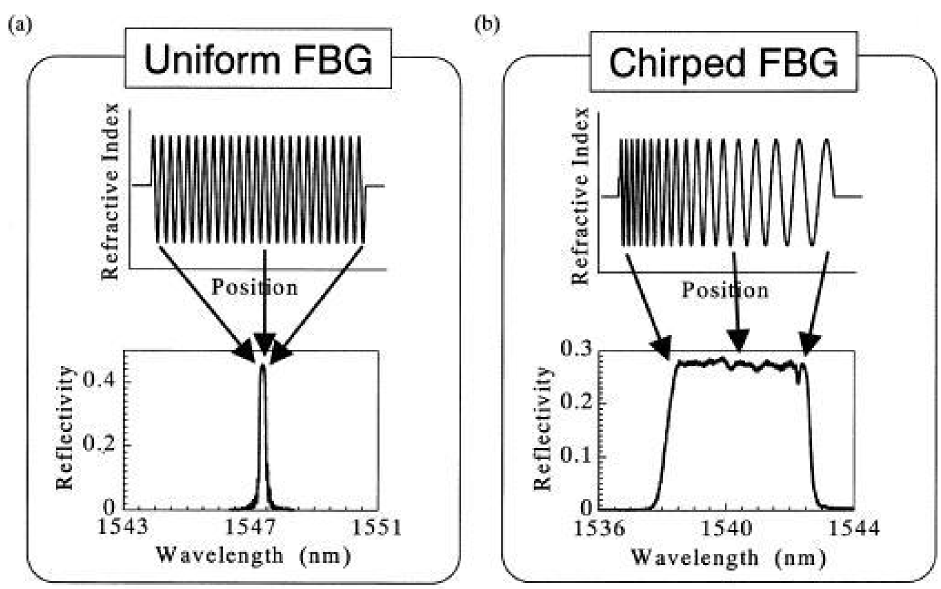


Figure:4 Uniform FBG (a) Chirped Fiber Grating (b).

- **Apodized Fiber Grating**

It is the fiber in which the amplitude of the refraction index modulation is not constant and varies with the location and position. The Equation (iii) can be shown which is the distribution function of refraction index.

$$\Delta n(z)= \Delta n_o[1+v\cos(2\pi z/ \Lambda_o)] \qquad \text{iii}$$

Here f(z) = Apodized function, for altering the amplitude of the reflection index along the fiber. The f(z) is also the raised cosine function or Gaussion function. Apodized Fiber Grating as compared to the Uniform Fiber Brag Grating is much better and received better properties. Like in reflection spectrum in restrained side lobes.

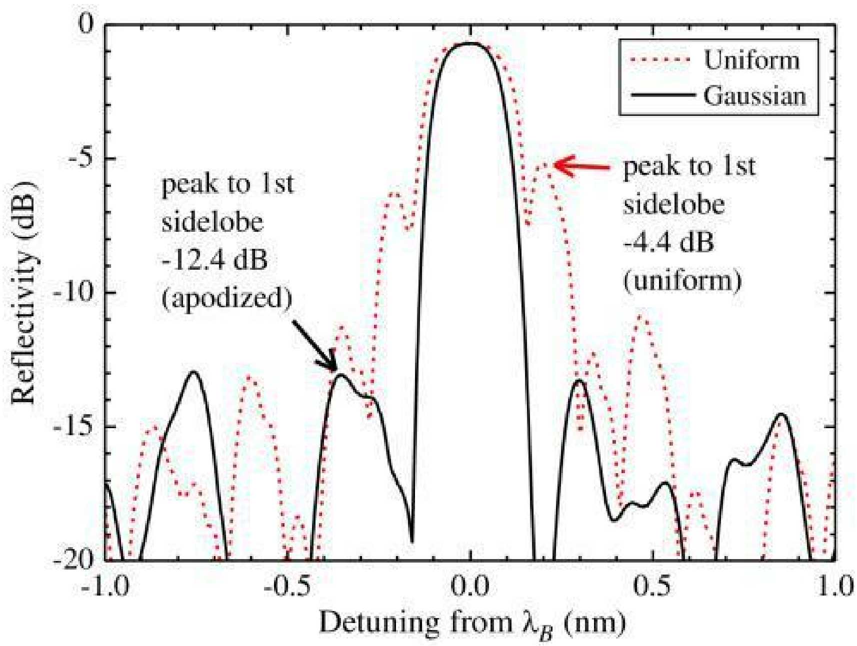


Figure (5). Gaussion Apodized Fiber Grating

- **Phased shift Fiber Grating**

In this fiber grating the refraction index changes discontinuously (phase shift). In this fiber grating phase shift is introduced, which means that there is a variation in refraction index. Figure (6) shows the phase shift fiber grating

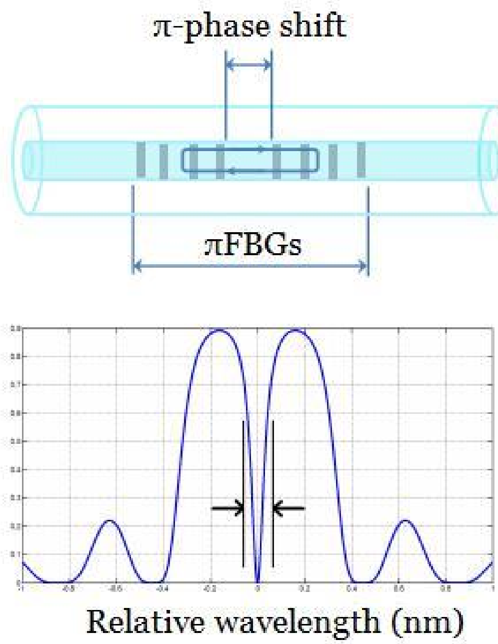


Figure:6 Phase Shift fiber grating

In reflection spectrum the narrow bandwidth window can be open. Here it means we have more than one choices for selecting the reflection wavelength in the single fiber grating.

2.2.2 Working Principle of Fiber Bragg Grating

Basically, the sensing phenomena of the FBG mechanism is of its changing refractive index of the core which produce the low disturbance. And it only effects the small part of the spectrum for the disturbance (approx. 0.05-0.3nm of the spectral width), while the other transmission light is not affected. And as a result, the incident wave will have reflected in corresponding frequency when the broadband light is transmitting in FBG. The center wavelength reflected back is as follows:

$$\lambda = 2n_{eff}\,\Lambda_o \qquad \text{iv}$$

where

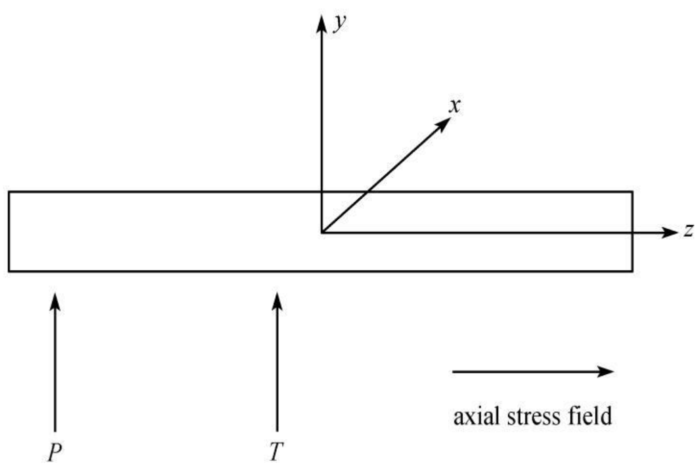
n_{eff} represents the effective refractive index of FBG fiber core, and Λ is the pitch cycle of FBG.

By means of total differential, above equation can be expressed as

$$\lambda = 2\, \Delta n_{eff} \Lambda + 2 \Delta\, \Lambda n_{eff}$$

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\Lambda}{\Lambda} + \frac{\Delta neff}{neff}$$

Under common conditions, as shown, the FBG sensor is in a state in which the axial stress field σ, uniform temperature field T, and isotropic fluid pressure field P are simultaneously functioning on it.



Sensing schematic diagram of FBG in free conditions

2.3 Distributed Temperature Sensor (DTS)

One of the optical fiber sensors which measure temperature is a Distributed Temperature Sensor (DTS). This optoelectronic sensor gives the continuous temperature profile along the length of the fiber cable.

Distributed Temperature Sensor (DTS) were first invented in 1980s. DTS can measure with high accuracy of temperature in +-1 Degree Celsius range, 0.01 Degree Celsius of resolution, 1m of spatial resolution and 30km of measurement distance. As optical fiber sensors are not on electromagnetic interference principle its utilization is common in power system, cables and oil and gas industry.

Detection of back-scattering light is the measuring principles of the DTS technology. Like utilizing following principles [14] [15] [16].

- Rayleigh
- Raman
- Brillouin

Short description of such technologies

2.3.1 Raman Scattering

Typical composition of an optical fiber is of doped quartz glass which is a kind of Silicon dioxide (SiO_2), the change in temperature along the length of an optical fiber sensors create the lattice oscillations. The Raman scattering phenomena is noted when the light falls on the thermally excited part of the fiber, interaction of the photons of the light and the electrons of the thermally excited area molecule cause the scattering of light called Raman scattering. And the shift of the scattered light is the spectral shift which is equal to the lattice oscillation's resonance frequency [15] [17].

The three components of the back scattered light are,

1. With wavelength of source the Rayleigh Scattering
2. With higher wavelength the Stokes component
3. With lower wavelength the Anti-Stokes component

The temperature dependent component is Anti-stokes whereas the intensity of the stokes component is insensitive to temperature. And the measurement of the local temperature is obtained by the ratio of anti-stokes to the stokes light [18]. Figure [7]. The approach of ratio was developed at Southampton university, U.K in 1980s [15]

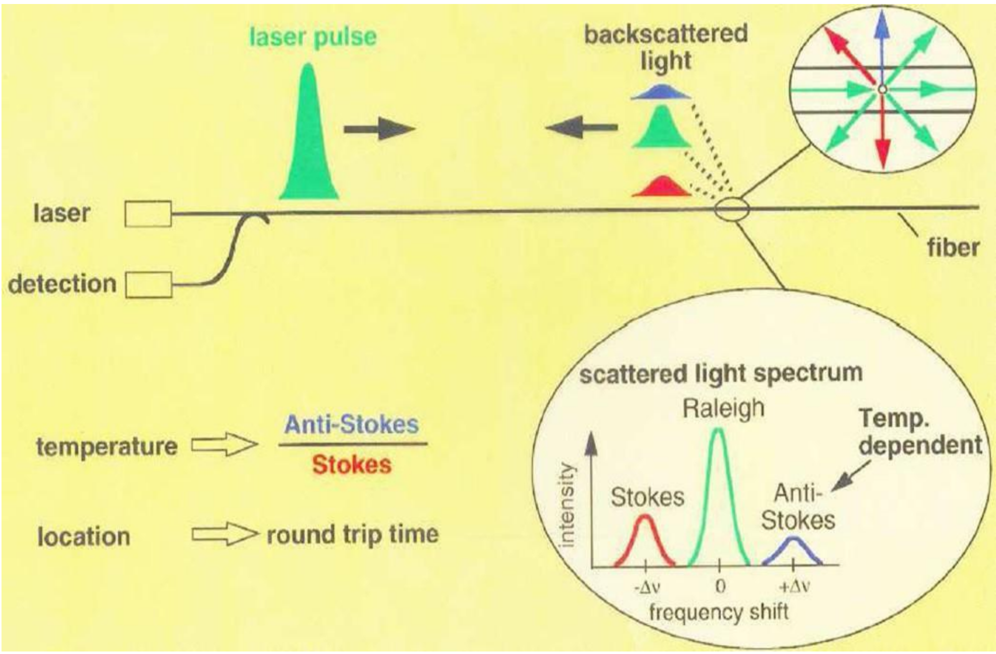


Figure: 7 the approach of ratio was developed at Southampton university, U.K in 1980s [15].

2.3.2 Brillouin Scattering

With Acoustic phonos of the medium there is a non-elastic interaction which cause an acoustic wave and the light wave scattering by this acoustic wave refers to as Brillouin Scattering [16] [19]. Both up-shifted (Anti-Stokes) light and down shifted (Stokes) Frequencies can be produced in Brillouin Scattering, given by [20]

Equation 1

$$\nu_b = \frac{\omega_b}{2\pi} = \frac{2nv_a}{\lambda_L} \qquad \text{v}$$

Where

w_b =Angular frequency shift

v_b=Brillouin Frequency shift

n=Refractive index of the fiber

λ_L=Free-space wavelength of the pump light

With the variation of strain and temperature the Brillouin scattering shift evolve linearly [20]. Which is given by the equation (vi).

Equation (vi).

$$\partial \nu_b = C_{\nu\varepsilon}\partial\varepsilon_z + C_{\nu\theta}\partial\theta. \qquad \text{vi}$$

for wavelength =1.55 micro meter, the Brillouin frequency shift's temperature and strain coefficients can be measured as $C_{v\theta}$=1.1MHz/K and C_{Vz}=0.048MHz/um [12]. Thus, both temperature and strain can be measured by Brillouin scattering based technique, but separately. According to the need of interest different coefficient can be apply.

The development of Brillouin scattering-based approach was in 1990s. In time-domain the scattering effect can be viewed. For example: (BOTDA) Brillouin Optical-fiber Time Domain Analysis [22]. And in frequency domain with higher spatial resolution for example: (BOFDA) [23] [24].

Table 1: Different DTS technologies Comparison

Scattering	Rayleigh [1]	Raman [2]	Brillouin [7]
Temp. sensitivity ($\%/^\circ C$)	0.54	0.8	0.01
Temp. range ($^\circ C$)	5 to 110	0 to 70	-30 to 60
Accuracy ($^\circ C$)	1	10	1 [6]
Spatial resolution (m)	1	3	3-5 [6],[10]
Fiber length range (m)	170	1000	51000 [6]
Measurement time (s)	2.5	40	4
Strain (μm)	-	-	100 [37]

2.3.3 Comparison

The summary of different Distributed Temperature Sensors Technologies (DTS) can be shown in table 1. According to the table the accuracy of the Rayleigh scattering is best, and it is limited to the length of the fiber. Now a day the length of the fiber is very crucial for example its application in underground power network systems. From this perspective Brillouin scattering offers good length range. With great sensitivity of temperature with time. Distributed strain measurement is also offered by Brillouin scattering as compare to other method. Therefore, for the replacement of Raman scattering, Brillouin is the best option [24]

2.4 Distributed Acoustic Sensors (DAS)

The DAS system is consisting of an Interrogator unit (IU) which is found at the surface connected with the fiber optics which is deployed in well at depth. Here the laser pulse is immitted into the fiber optics by the interrogator unit which travel though out the fiber optics length and IU receive the backscattering signals.

The deformation of the fiber optics is determined by the summation of back scattered signal of two location of DAS channels and by its phase lag analysis. So, by this approach we can determine how much and where the optical fiber is deformed. The strain directly controls the phase lag, or we can say that the phase lag is the function of the strain.

The cause of the deformation of the fiber is the seismic waves. The gauge length can be defined as (nearing the DAS channel the two locations distance) which is calculated for the acquisition. The interrogation of the phase- lag can be done everywhere throughout the length of the fiber, so it means that DAS is not a discrete sensor but continuous sensor.

In Figure 8 the DAS working principle can be seen. As the light emit into the fiber optics and experience the backscattering effects and at the beginning gauge length it is S1 blue and at the end It is S2 blue. As the fiber get strained so for the second light pulse emission the backscattered signal S1 becomes red and S2 becomes red as well. And between S1'+S2' and between S1+S2 the phase lag is directly related to the strain.

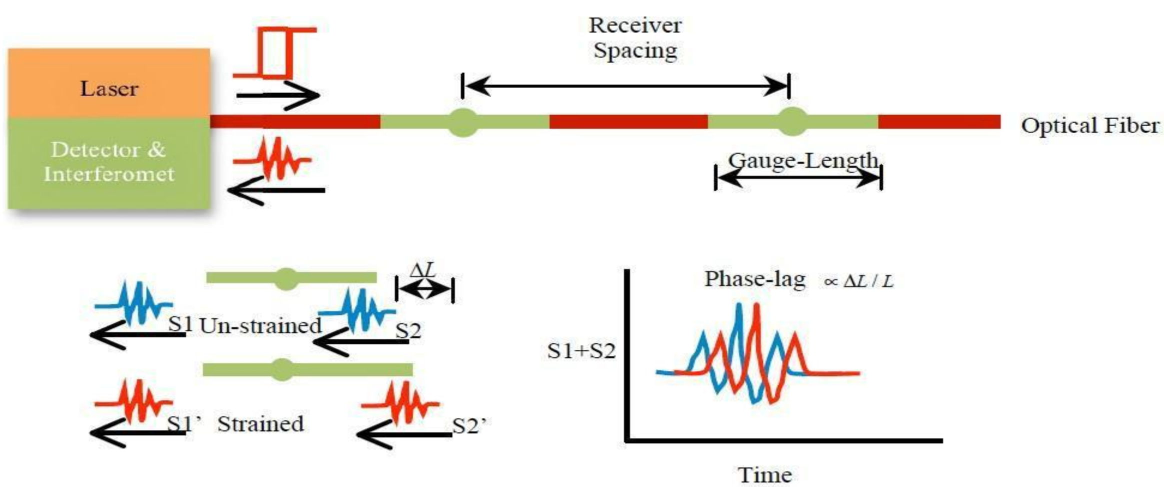


Figure 8. Working Principle of DAS System

DAS performance is not relay on the point sensors. Because it is the distributed sensing system and not dependent on multiple fibers. As compare to the seismic frequency the light pulse generation rate is much higher approx. 10-100kHz. The S/N ratio is the function of the rate of the light pulse. But the length of the fiber limits the generating rate.

As DAS is continuous sensor and it can be taken as the array of receivers. And the distance between the two arrays is approx. 1m. For optimizing performance, the parameters like rates, spacing and the length of the fiber can be change.

Chapter # 3

Applications of Optical Fiber Sensors In oil and Gas Industry

This chapter will discuss the detailed overview of FBG, DTS and DAS application in upstream area of petroleum industry. As rapidly growing petroleum industry, increasing the profit and yield demands advances in new technology for low cost or cost-effective production in important areas of the exploration and production sector.

3.1 Application of Fiber Bragg Grating (FBG)

In this portion the application of Fiber Bragg Grating is discussed more particularly in well-logging. Its application in seismic exploration can measure many parameters like pressure, temperature and acoustic waves in harsh environment. In seismic exploration the Fiber Bragg Grating is require to show high sensitivity over the wide range of vibrational frequency i.e. from 5Hz to 2.5kHz, which hold the most necessary Geological information.

- **Applications in Downhole**

The naked FBGs are useless to measure the physical parameter like Temperature and pressure in the very hostile and harsh downhole environment. It must be protected by coating and packaging without attenuation of sensing properties. The one of the recent technique is the application of alloy material of Nb-40 Ti-5.5 Al for packaging of FBGs. The advantages of this material are the small elastic modulus, good resistance against high temperature, pressure and erosion by H^+, Cl^-, CO_2, H_2S in downhole. The structure of packaging is fabricated with alloy and then the FBGs sensor fixed in the packaging structure with a typical gel of a silane coupling agent which contain 4% Vol SiO_2. The customized glue of polypropylene rubber adhesive increases the stability over high temperature range of -20 to 400 C. It can be shown in Figure [9].

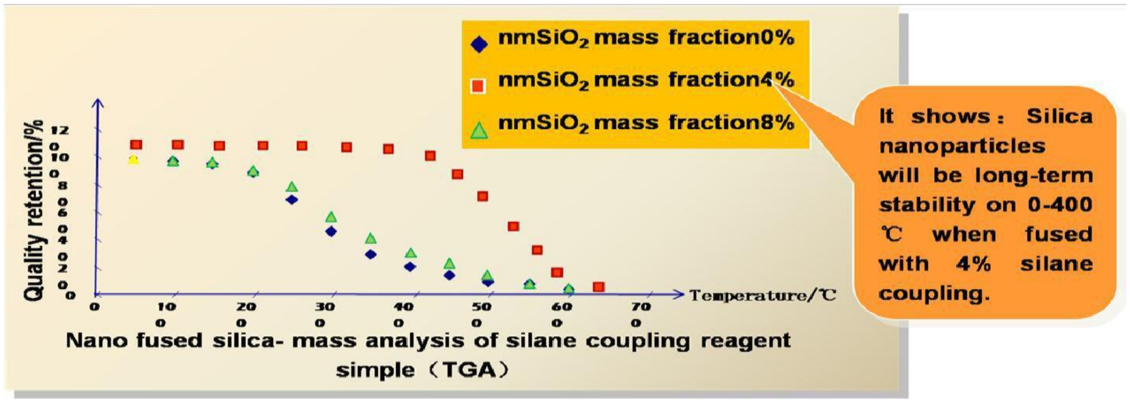


Figure 9. The sample with the particles of 4% nanometer SiO2. Testing result of the glue

The fiber Bragg Grating Sensors with all packaging structure are now in practice in well logging for measuring the temperature and pressure of water, oil and gas inside the well. Series of sensors can be seen in Figure [2].

Figure:10 Series of FBG sensors

For logging and sensing vibration, pressure and temperature down deep wells it is very mandatory to avail the sturdy fiber cables which can bear high pressure and temperature.

In the month of September 2010, the team of Xueguang Qiao and Zhihua Shao, and other 16 team members performed downhole testing at Liaohe Oilfield of Qi-40-Guan-23 for finding the performance of Fiber Brag Grating Sensor under downhole harsh environment, which can be seen in Figure [3]. And they used the fabricated fiber Bragg grating sensors which can detect the temperature (0-350C) and pressure ranges from (0-100MPa),

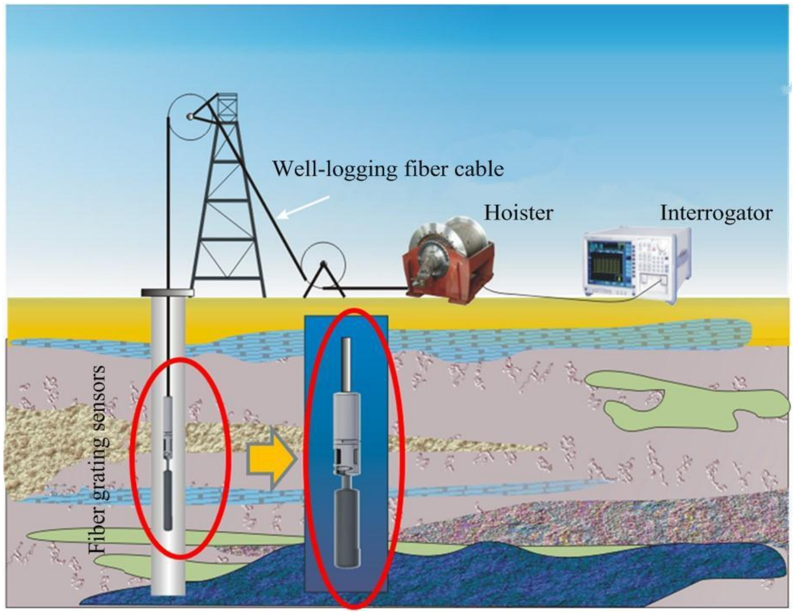


Figure 11. Downhole testing Diagram

Pre-well logging all the mandatory preparation work was completed. With the home-designed cable the sensor was connected. That armored fiber was very important in determining result consist of dual layer tube for the fiber safety. The tube was surrounded by that aramid fiber which named as a buffer layer, the main role of this layer was to protect from shock especially external. With the cable the FBGs was run into the downhole (can be seen in Figure 4) and at the surface the monitoring equipment's monitors variations of pressure and temperature.

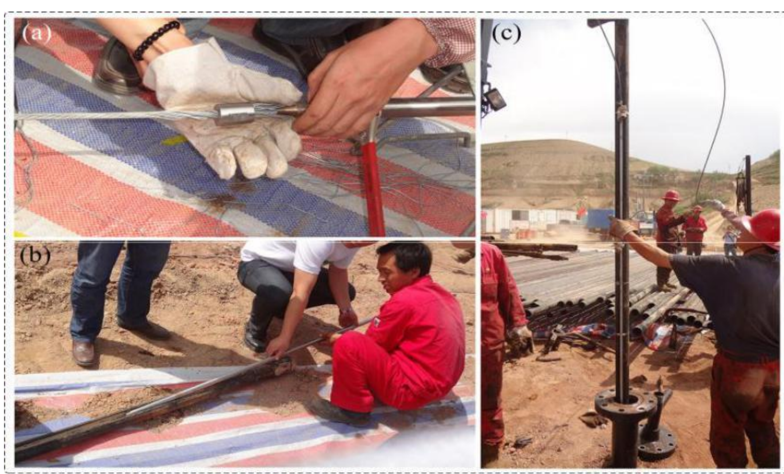


Figure 12. Well-logging field: (**a**) Downhole cable; (**b**) Tied to the downhole tube; (**c**) Sensor down well process.

Figure 13 shows the temperature profile of 1100m deep well. The profile is just exact like the profile taken by other temperature thermometer. It is crystal clear that the region between 800m to 1000m there is the huge temperature spike, the maximum temperature recorded between this interval was 240 C which is tremendously huge than the recorded temperature between surface and 800m which is 40 C to 50C. It is confirmed from this discussion that the FBGs with fabricated coating and packaging can record temperature downhole.

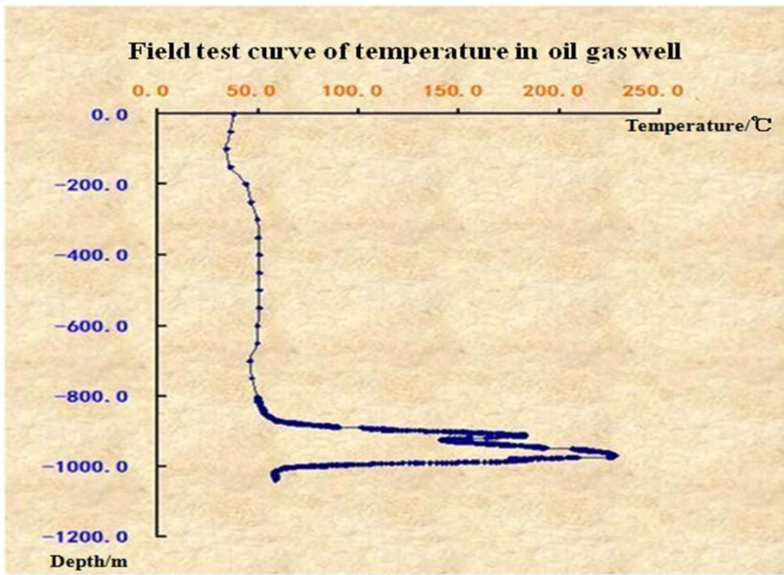


Figure:13 Down to 1100 m depth of well hole, measured by FBG sensors Temperature distribution

With the collaboration of China Petrol Logging (CPL) Xueguang Qiao and Zhihua Shao with other member of the group in the month of July 2012 tested FBGs for the measurement of liquid level and temperature and detect almost accurate values at almost 1400m depth of the well in Jinbian County in Shaanxi Province China but the most prominent advantages of usage of this fabricated FBGs is its sensitivities of pressure and temperature which is 30.9pm/MPa and 12.9pm/C. Moreover, the fabricated FBGs can withstand the operating pressure and temperature of approx. 40MPa and 150C with the resolution of 5m of liquid level and 0.1 C of temperature. The equipment for observation were equipped with alarm, halt machine and reset depending on the downhole situation.

The observation of the FBGs can be observed in the following Figure [14] which was basically pressure, temperature and liquid level profile of 1000m depth of well. Here the result can be seen that the variation of temperature from 18.4 C to 29.8 C and 0MP to 1.87MPa in the region of 0 to 1000m depth of the well which have same response as of the other Electro-Magnetic sensors.

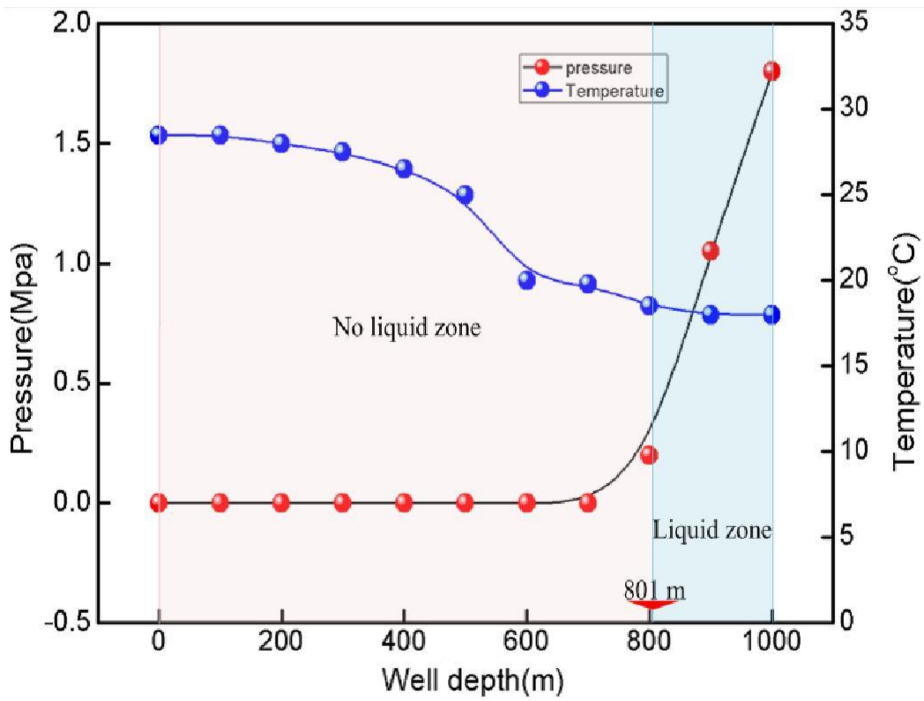


Figure:14 Downwell pressure, Temperature and liquid level distribution

Following is the table which shows the complete pressure and temperature data of the tested field by Xueguang Qiao and Zhihua Shao and other members.

Table 2. Details of a site

Site	***Time***	***Measuring Duration***	***Depth***	***Pressure***	***Temperature***
Jinbian	2012 July (6-15)	6h	approx. 2000m	0-1.87Mpa	18.4C-29.8C
Liaohe	August 15, 2010	6.5h	approx. 1638m	0-15Mpa	36C-241C

3.2 DTS Applications

Application of Distributed Temperature Sensing system common in petroleum industry. Installation of DTS are categorized as Permanent, Semi permanent and Re-trievable.

Its application in oil and gas wells as a monitoring of temperature log. And effect of liquid flow could be related from that temperature log when well is shut in. In static rathole the cooling effect of gas entering the channel can be detected. At the same manner the cooling effect in water injection could be identified in temperature log. Monitoring of well on a platform and in production well the steam breakthrough is done by DTS system. As well as the startup of the motors and Electric Submersible Pumps (ESP) are detected by Distributed Temperature System (DTS)

In 1984 the DTS concept that apply the Raman Backscattering. In Raman Backscattered signal by comparing the intensity of anti-stokes band with the stoke band the local temperature evolution can be obtained. Here the intensity is related to the temperature. As the intensity is a function of the temperature but anti-stokes intensity also depend on other factors like optical path losses. But to reimburse the losses there is an introduction of reference signal: stokes band signal. And these loses are removed practically by taking the ratio of stokes and anti-stokes signal. Due to the difference in wavelength of the signals the compensation of losses is different. To overcome this issue many techniques are proposed [32] [33].

Based on number of samples averaged and spatial resolution, the temperature resolution of DTS is 0.05 °C and with ±0.5 °C of accuracy.

In 1990s for Steam assisted gravity drainage (SAG-D) method to monitor temperature along the length of the well, the distributed Temperature Survey was used in petroleum industry to monitor temperature. [34] [35]. In this method (SAG-D) two wells are drilled horizontally and parallelly in heavy oil reservoir

Among two wells one of them is for injection of hot stream for heating the high viscous oil for making mobile and other well is the production well. Now here the application of DTS is to monitor the temperature along the total length of the producing well.

The utilization of DTS has been increased for the monitoring of downhole fluid flow [36] [38]. Which create gain and lose of heat in a well. This downhole fluid flow causes the evolution of temperature profile of a well.

Hydrocarbon production in oil/gas well is mostly from multiple zones. And the availability of a few information not which zone is producing, and which is not is common. But DTS helps in allocating the zones basis on temperature difference. In a well if there is no flow then the temperature of the well will follow the natural geothermal gradient. Once the production starts and the hydrocarbon enters the borehole from the formation the production zone temperature varies due to the Joule-Thomson effect (The fluid temperature drops due to the sudden change in pressure as fluid enters from formation into the borehole) and when production halts then the temperature goes back to its geothermal trend. By combining this data of DTS and other pressure data the result will be the good interpretation of the production zone [37] [39].

DTS also identify the type of the fluid flowing into the well. Due to the difference in Joule-Thomson effect between oil and gas the sign of the temperature also varies. Which means the for liquid and gas the temperature increases and decreases respectively. Identification of the pay zone by the analysis of the DTS data is possible [38]. But suboptimal situation occurs when there is a gas production in an oil well.

- **Monitoring of Acid Treatment**

The other application of the DTS in upstream sector is monitoring of acid treatment. In this treatment the acid is injected for stimulation job: Enhancing formation permeability [36] [39] [40]. As here acid enters in formation and due to the nature of exothermal process the temperature of the zone increases.

3.3 DAS Applications

This portion of this section will discuss some of the application of Distributed Acoustic Sensing in upstream Sector of the oil and Gas industry.

The very first uses of optical fiber sensors downhole in oil and gas industry took place came about in the nineties and at the first this technology was related to the single-point temperature and pressure sensors [25]. With the passage of time the technology of optical fiber sensing was started growing and a new technique of distributed sensing was shaped (Figure 7). Primarily, in the middle of the decade DTS was fashioned for monitoring downhole and later this technology enters in commercial area of petroleum industry in installation of oil and gas well in 1995 and in 2002 more than 100 well were equipped with this technology [26]. Distributed Acoustic Sensing (DAS) is a very advance technology.

The DAS system is installed into the well by running the telecom fiber and converting into everlasting array of microphones. This is done by detecting the vibro-acoustic disturbances and mechanical movement along the length of the optical fiber. Most particularly the DAS system adopt Coherent Optical Time Reflectometry [C-OTDR] technique which emit short, successive pulse of light and observe/monitor the backscatter of the signal because of the anomaly in the glass core [27]

According to the Tanimola and Hill (2009) the component of the backscatter signal used in DAS is the Rayleigh backscatter.

3.3.1 Deployment of Fiber

In DAS system the optical fiber used in multiple ways.

- ***Running Outside Casing***: Here in this situation the optical fibers clamped outside the casing and it can be used in downhole or subsea as a permanent monitoring application with highest data quality and highest cost.

- **Running *Outside Tubing***: The optical fiber runs outside of the tubing this installation is the semi-permanent measurement with lower quality and cost.

- **Running *inside Tubing***: The optical fiber in this state deployed inside of the tubing. The advantages are easily retrievable with lowest cost, but the cons are the noisier data as compare to the above two types of installation.

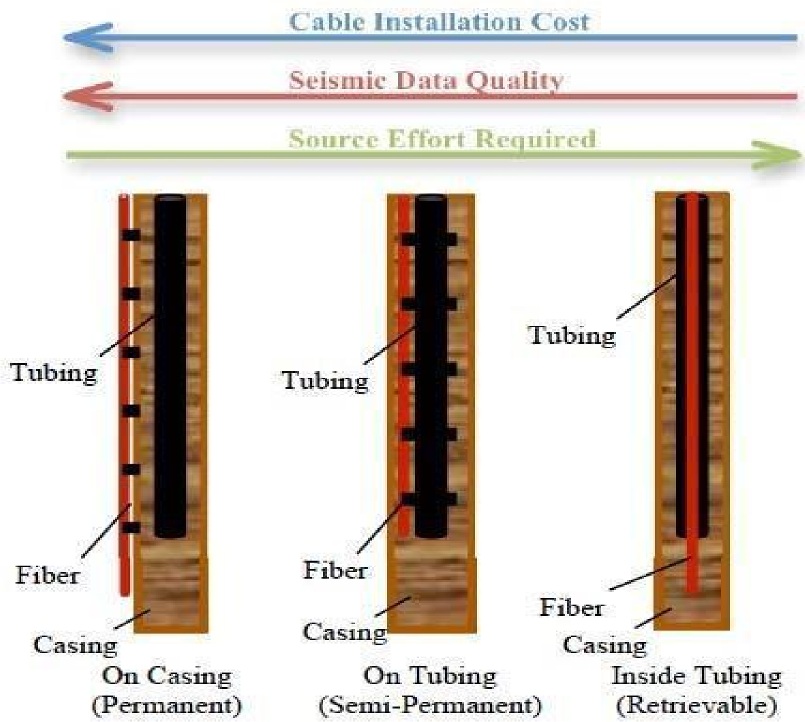


Figure: 15 Compares the data quality, cost and source effort of three deployment types.

The energy required for the receiver to detect the signal is stated here with "***Source effort***". After the trial in Louisiana (US) it was cleared that the meaningful seismic signal can be recorded if the fiber is run into tubing.

3.3.2 Applications of DAS with Geophysical Measurements.

Alongside with its advantages and application in construction, production and completion. Its importance in geophysics matters a lot like its application in Vertical Seismic Profile (VSP), reservoir and well surveillance, micro seismic measurements and HF monitoring all these applications is witness that DAS is now replacing geophones. Figure (16) shows the application of DAS over the life of well.

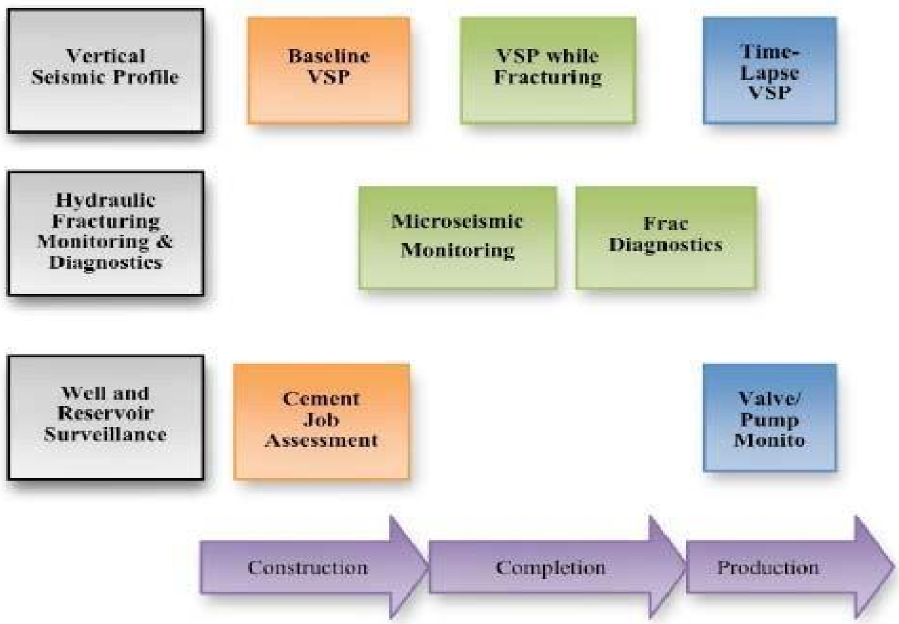


Figure 16. Multiple applications related to DAS.

- **Micro-seismic Monitoring**

Shell first apply the DAS for detecting micro-seismic event [29,30]. They deployed both DAS system and geophone in the field trial in the same well for comparing during the stage stimulation the sensitivity and ability of detecting the micro-seismic event. As compared to DAS the geophone coverage is limited. In figure (11) the detected micro-seismic event of both DAS (grey) and geophone (red) can be seen. On DAS record at the apex of the hyperbola the P wave disappeared due to the weak transverse sensibility. But as compared to the geophones DAS gives entire wells the full coverage.

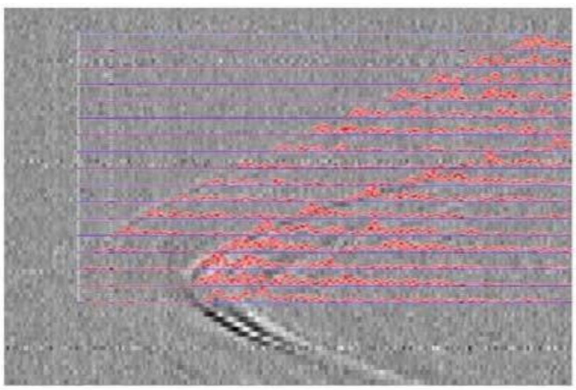


Figure: 17 Detected micro-seismic event on both DAS (grey) and geophone (red) data

The crucial pros of this technology in micro-seismic application is the deployment of the fiber optics in to the treatment well. And this application provides the readings of micro seismic activities where it is not possible to take its reading usually.

More over the determination of the exact location of the micro seismic events is also possible with the help of the observation and treatment wells information.

The drawback of the single component data of micro seismic is the lack of information about azimuth because it only provides the distance of the event. As the micro seismic source cover a circle and if the deviation of well into the horizontal direction occurs then the location of the source can be narrow down. Only possibility if the data is recorded in by separate DAS channels.

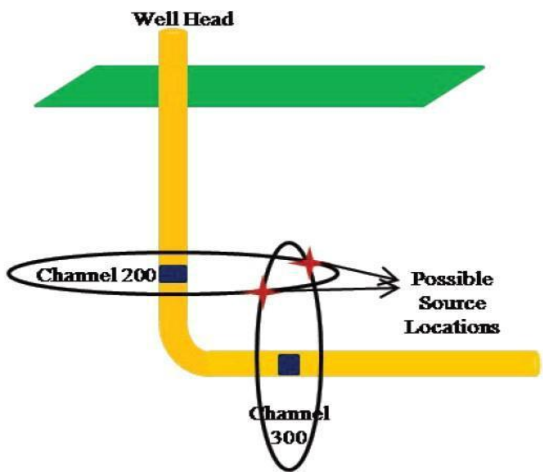


Figure :18 Narrowing of the micro seismic source

- **Monitoring and Diagnosis of Hydraulic Fracturing**

The common practice for the observation and diagnosis of the HF is by well head pressure, rates. pressure of the downhole and the tracers which are active radioactively [31]. But getting such type of data is very difficult from reservoir with complexity and with the lower investigation radius. But to overcome this situation the combination of DTS and the DAS data helps in investigation of the fracture growth and initiation in real time.

Basically, the monitoring and Diagnosis of the HF by means of the DAS is the rates and volume assessment of the injection fluid. Such information related to the HF is important for its modeling and diagnosis. The combination of DTS and DAS data is the helping factor for the controlling and monitoring of the traditional HF.

- **Reservoir and Well Surveillance**

Beside the monitoring of HF and other application. The quality of the DAS data is also that it can replace the PLT Production Logging Tool. For measuring the production in downhole and injection performance into the well and reservoir.

As due to the cost factor and operational risk factor the well surveillance data cannot be obtained from PLT. And may case the delay of production in deviated and horizontal wells. Its application related to the surveillance and well production monitoring includes the readings and graphing of the injection profile, production profile, well integrity and multiphase flow.

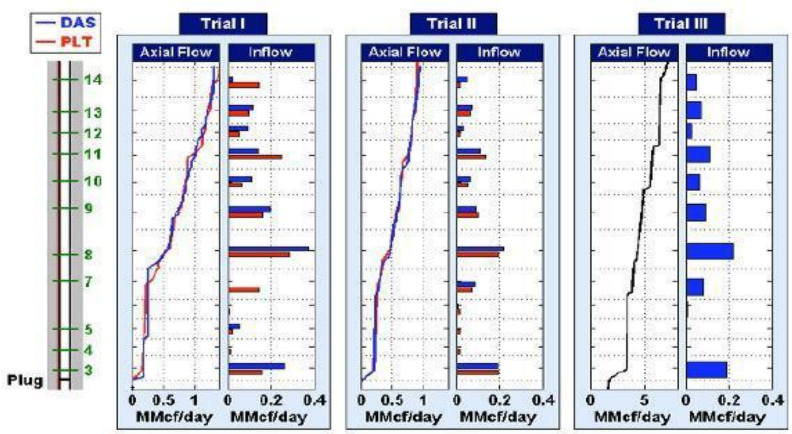


Figure 19. shows the Production profile. Both PLT and DAS

Chapter# 4

Critical Analysis

4.1 Analysis of Fiber Bragg Grating

Fiber Bragg Grating is very sensitive over a wide range of frequency from 5Hz to 2.5KHz, these frequencies are very important and contain a lot of information related to the subsurface geology. With the installation of the mechanical transducer in FBGs enhance the amplitude and frequency response of sensors. And sensors must resist and stable in high pressure and temperature, up to 40Mpa and 175 ◦C. This portion of the thesis will discuss the sensitivity of the Fiber Bragg Grating.

- **High Temperature Sensors**

In Ultra-deep well-logging, pipeline field monitoring and oil/gas well-logging temperature is a key parameter. In deep well it is important to monitor temperature. Fiber Bragg Grating for stability ad calibration the monitors of FBG needs heat resistant packaging materials. There are many other important methods and technique for the temperature resistance for example changing the composition of the glass [41] [42], like annealing prosses [43] [44], and using femtosecond lasers for inscribing gratings [45] [46]. After fabrication the temperature measurement reached up to 1100◦C, and for reducing the cost the researchers still working on new methods.

The best example of the Fiber Bragg Grating which achieve 1100◦C is a regenerated Fiber Bragg Gratings (R-FBGs). In (R-FGBs) as annealing temperature increased or reached towards the regeneration point a seed grating is steadily erased. The grating grows again with continuous increase in temperature [47] [48]. As compared to seed FBG the RFBG shows the narrower spectral bandwidth after regeneration which is very aiding factor in enhancing filtering Figure 20.

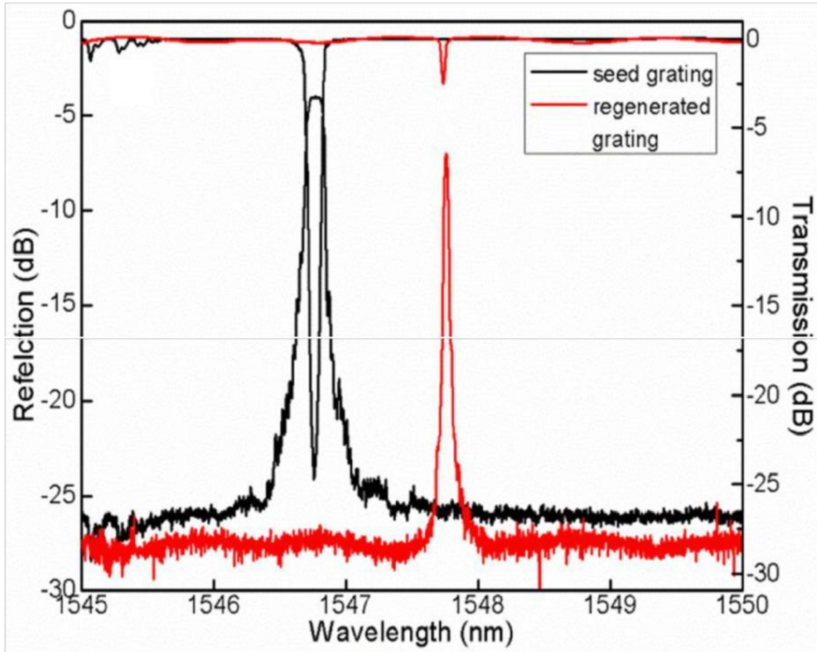


Figure: 20. Reflection and transmission spectra

But the reflectivity is lower than seed FBG. Another issue is the heating process which is very complex, and it is mandatory to observe and monitor spectral response. As compared to the conventional FBGs the RFBGs are much weaker mechanically. Table 1 shows the comparation between different types of FBGs.

- **High Pressure Sensors**

From 1930s the downhole pressure measurement is carried out by means of pressure gauges [49]. The mechanical gauges were very hard and robust structure, but the accuracy was lower than 40psi. electronic pressure gauges were introduced in 1970s based on strain gauges. These gauges were simple and reliable but again their accuracy was not stable and adequate. And these electronic pressure gauges have the same drawback as of thermometer. But fiber optics are more reliable than other gauges up till now. And till now many fiber optic sensors have been introduced for the downhole measurement for example: DTS-based pressure techniques [50], intrinsic and extrinsic Fabry-Perot interferometers [51] [52]. Figure 21 shows the FBG pressure Sensor. Pressure measurement is carried out in FBG by detecting the shifts in peak of the Bragg resonance. But the measurement of the temperature with the pressure create the cross talk and to avoid such degrading effect on the accuracy of the pressure measurement there is the solution of applying the cascaded dual-FBG structure to measure the pressure and temperature simultaneously [53].

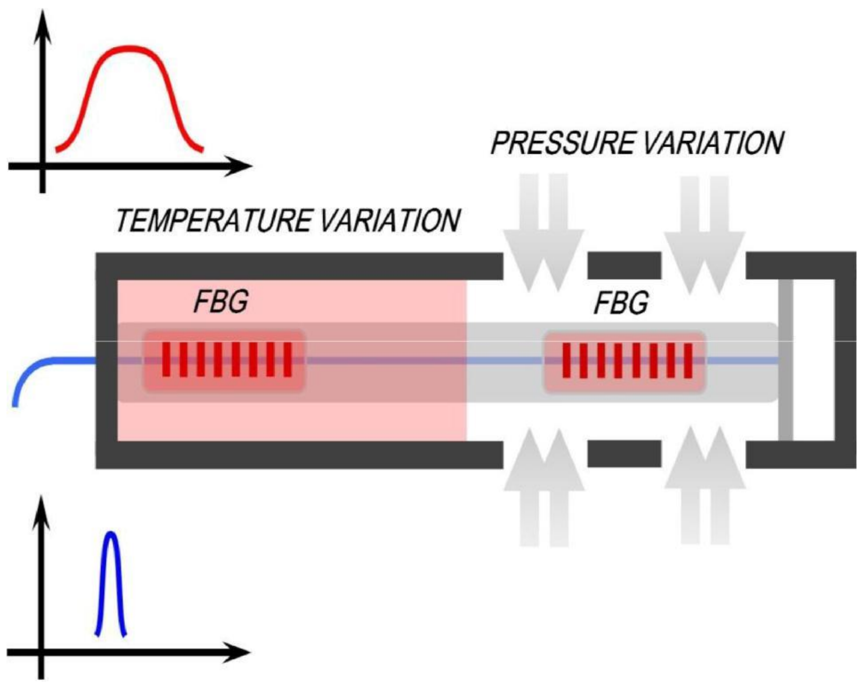


Figure: 21 Shows the FBG for simultaneous measurement of pressure and temperature.

4.2 Analysis of Distributed Temperature Sensing

This portion of the thesis will discuss the analysis of the Distributed Temperature Sensing data of two CO_2wells in an intensive detailed area of study of an onshore gulf coast of CO_2 injection site (there CO_2 have been injected of more than 5 million metric tons). The zone of injection is the lower Tuscaloosa formation with 3185m to 3206m depth range.

- **Field Discription**

There are three wells were included in deatiled area of study which are (one injector well (F1) and other two wells (F2) and (F3) were observation wells abd the distance between the injector and observation wells were 70m and 112m. and the Distributed Temperature Sensing optical fiber were deployed along the length of the observation wells for observing and monitoring the temperature in the presence of other monitoring tools like conventional guages. Measurement of the temperature were required for every meter along the length of the wellbore with the time duration of minutes 2 – 15 for one year from 2009 November to 2010 November. With in this duration aprox 4 hundred million temperature readings were recorded. Along the adjoing zones and injection intervals the data were analyzed. The variation of the observed temperature shows the timing of the temperature disturbance and vertical distribution.

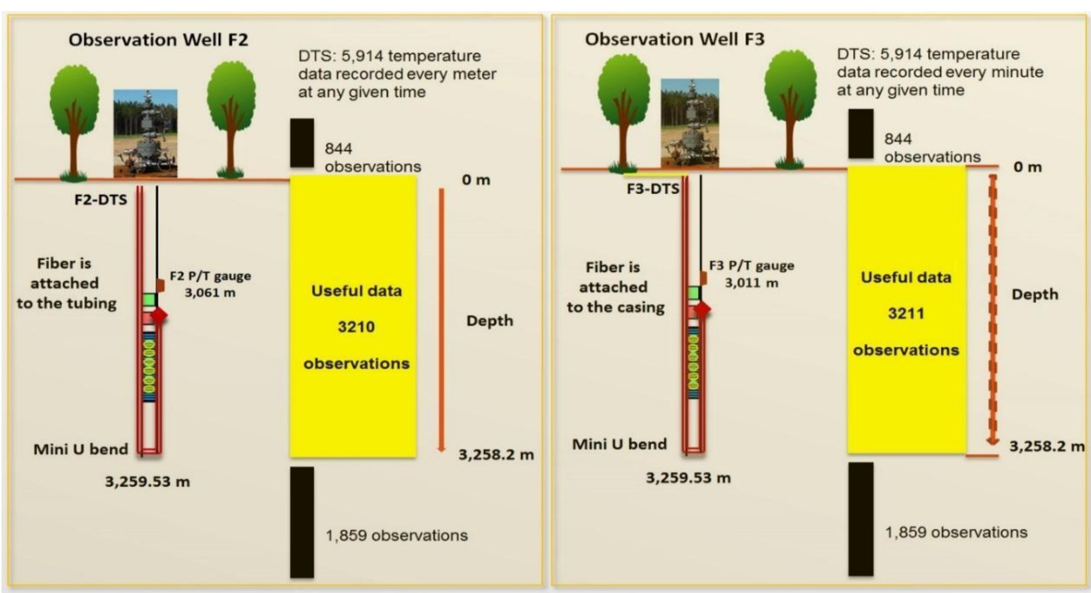


Figure 22. Location of the Distributed Temperature Sensing and Spacing .

- **DTS Data Validation**

At shallower depth the resoulution of the Distributed Temperature Sensing Technology is of 0.0045 °F [2]. As in this study the depth of the investigation is much deeper than 915m and for validating the temperature recording accuracy the author compared both DTS data reported and the gauge recordings in F2 and F3 wells. These guages were installed at the depth of the 3060 meters and in injection wells at 3185 meters. The same temperature trend during first three month were recorded by both type of instruments in F2 well. In the month of novemebr 2009, 14th the coil tubing operation caused the guage to record a temperature increase of 1.32°C and the Distributed Temperature Sensing to read an increase of 1.5°C. Both gauge and DTS recorded a decrease in temperature which last one week. Hence, it can also be monitered the decrease in data of DTS from february 2010 and the diffrence from gauge temperature of 7.2 °C. Due to deviation of instrument drift which basically the variation in measurement when measured a same property under similar condition. Similarly, the drift means the loss of calibration. Figure 2 shows the data recorded.

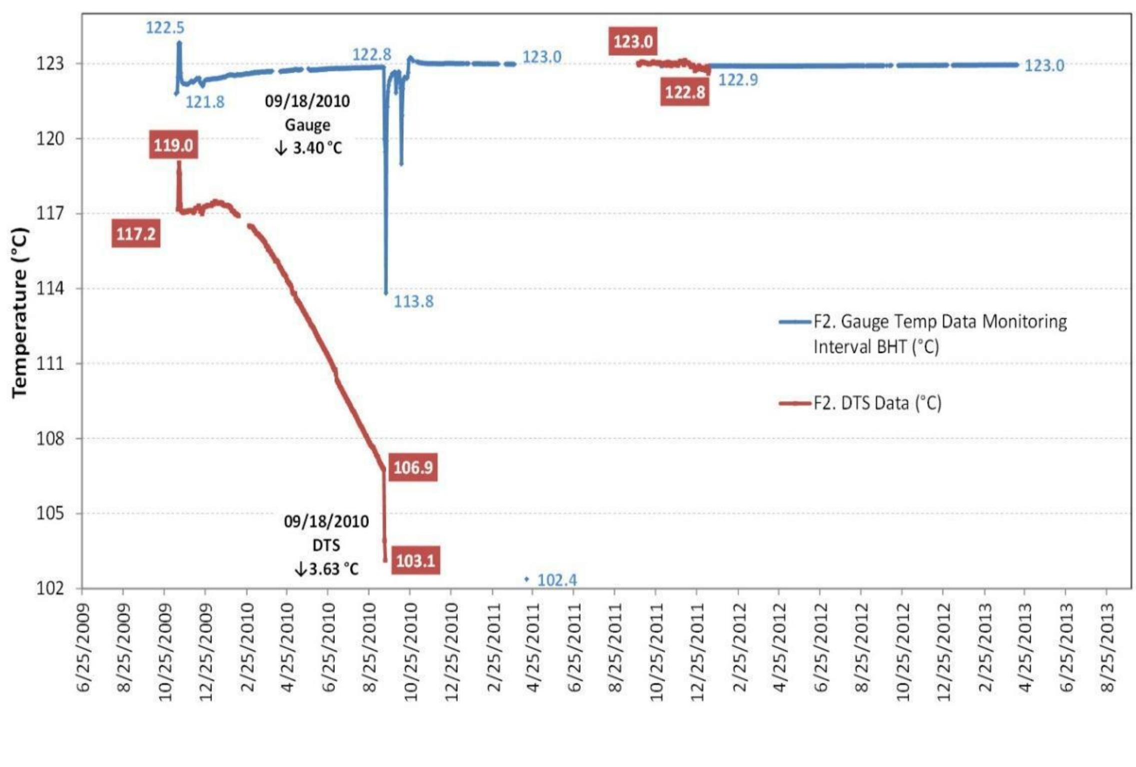


Figure 23. DTS and gauge temperature data at the depth of (3061m) in F2 well.

Similary, in F3 the similar trend of the temperature reduction was recorded in initial period till November 2010. In this period the change of temperature recorded were induced by external facors like workover and these temperature jumps were recorded in both instruments. Like on 2009 December 9th for pumping nitrogen at 300scf rates with coild tubing in F3 and like wise on next day a variation in temperature were recorded in both instruments. Similarly, on 10th September 2010 F3 well were killed by means of workover job the temperature readings were recorded in both gauge and DTS. Gauge recorded a drop of 8.35°C and DTS recorded a drop of temperature of 9.5°C. there was a huge gap of temperature is observed between November 2010 and September 2011 in DTS data.

Data recorded by DTS in september 2011 was very different from data recorded by gauges for this reason DTS data at the depth of AZMI after November 2010 was not validated. The only reason was becasue of the instrument loss of calibration.

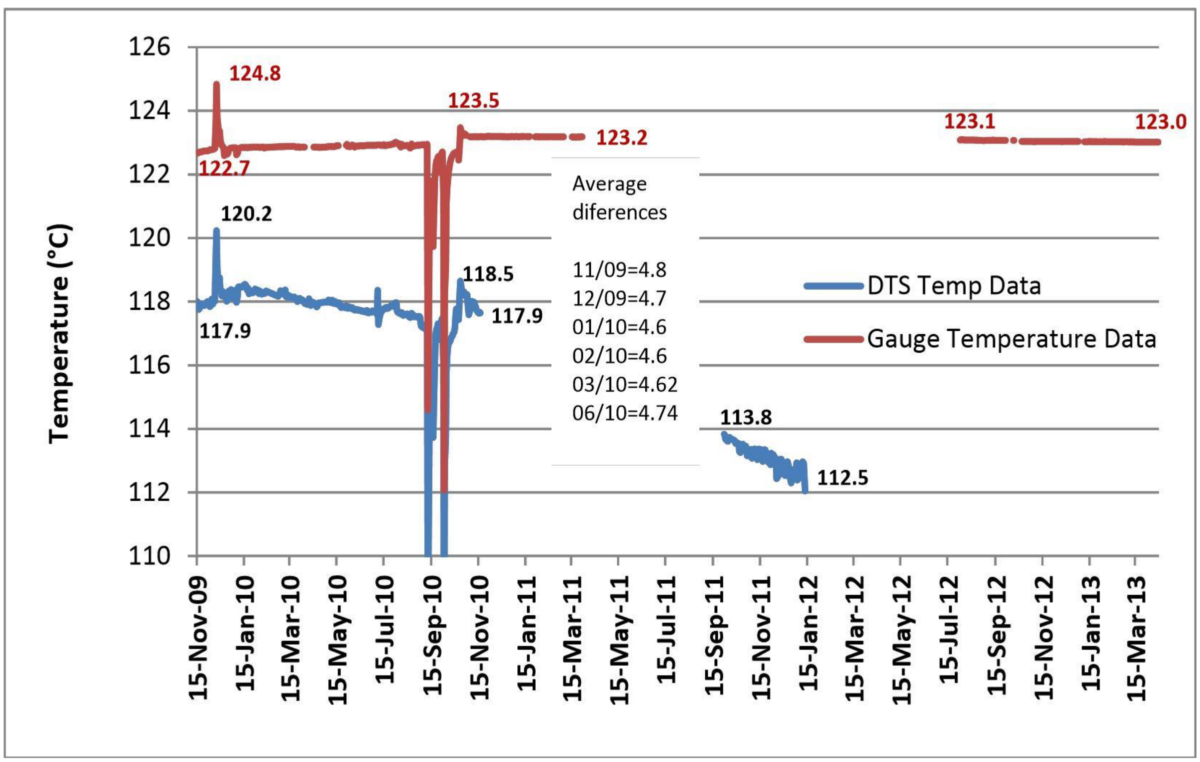


Figure 24. Gauge temperature data and DTS data at the AZMI (3,061 m) in F3

- **Data Analysis of DTS**

Distributed Temperature Sensing Temperature Observation at F3

Evolution of temperature recorded are shown in Figure 4. The temperature gradient which was undisturbed before injection used as benchmark for recorded temperature profile. There were two necessary temperature trends were observed.

With time steeper gradient slope shows the cooling trend. In the beginning of 2010 January the gradients deviated from reference gradient towards much cooler temperature. After two in AZMI zone the temperature zone had cooleed by 5.6°C. At the injection zone also, reduction of temperature recorded aprox 11.4°C w.r.t max temperature was monitored in January 2010 (123°C). This trend of lowering of temperature is due to the injection of CO_2.

During the month of August, September and October an unexpected high temperature trend was observed and disappear in mid-June.

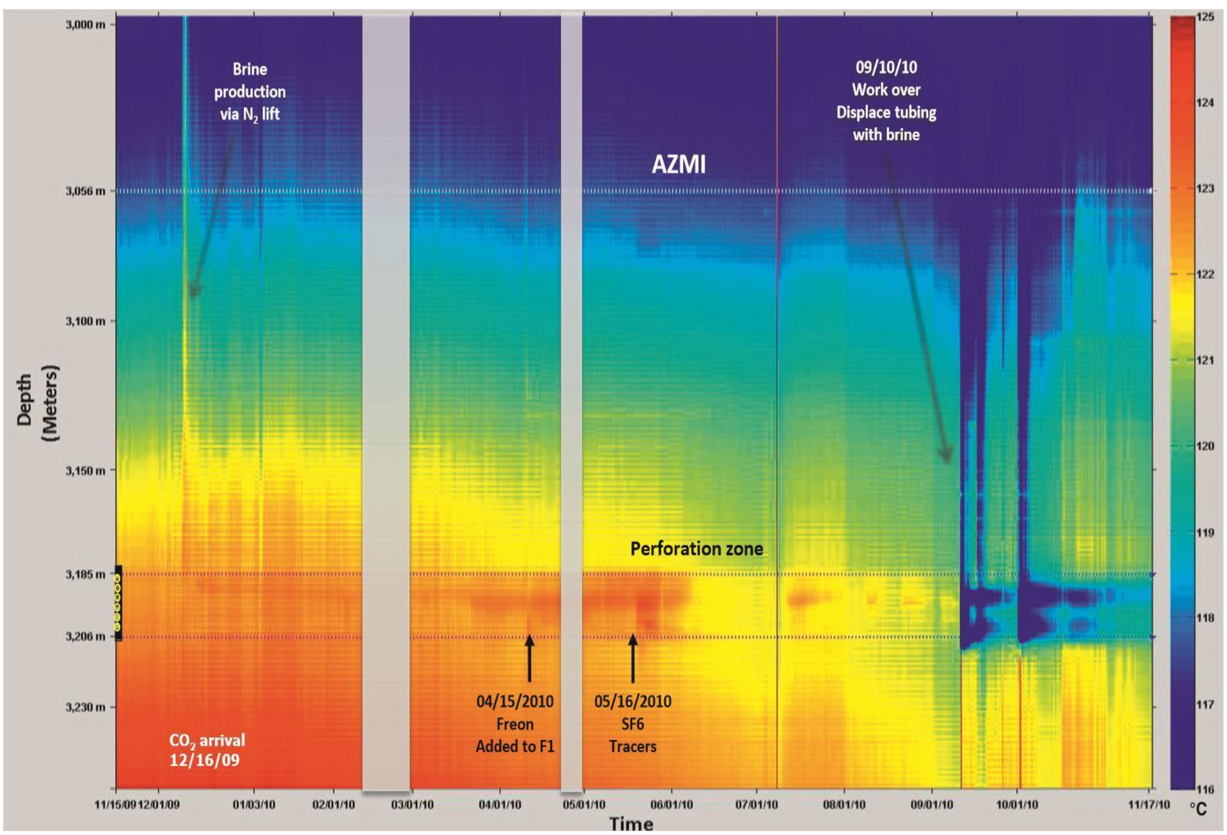


Figure 25. Temperature variation, vertical distribution, and timing of temperature evolution from Nov. 14th 2009 to November 17th 2010 at observation well F3.

- **Distributed Temperature Sensing Temperature Observation at F2**

Figure 26 shows the temperature change for the given period of collected data. The reduction of the temperature was also noted in his well. After one year this cooling trends changes. The temperature increases by 19.8 °C from (103.3°C to 123.1°C) in one year from september 2010 to september 2011. At the injection zone this trend of increasing temperature was also noted with the increase of 24.1°C to reach 125.7°C in one year. For the period of November 2009 to August 2010 the similar performance of the temperature gradient noted and temperature recording along the wellbore. The temperature recording in september along the wellbore shows the shift down, this indicate workover job. Figure 6, shows the temperature gradient with the shift due to N2 injection in mid-November.

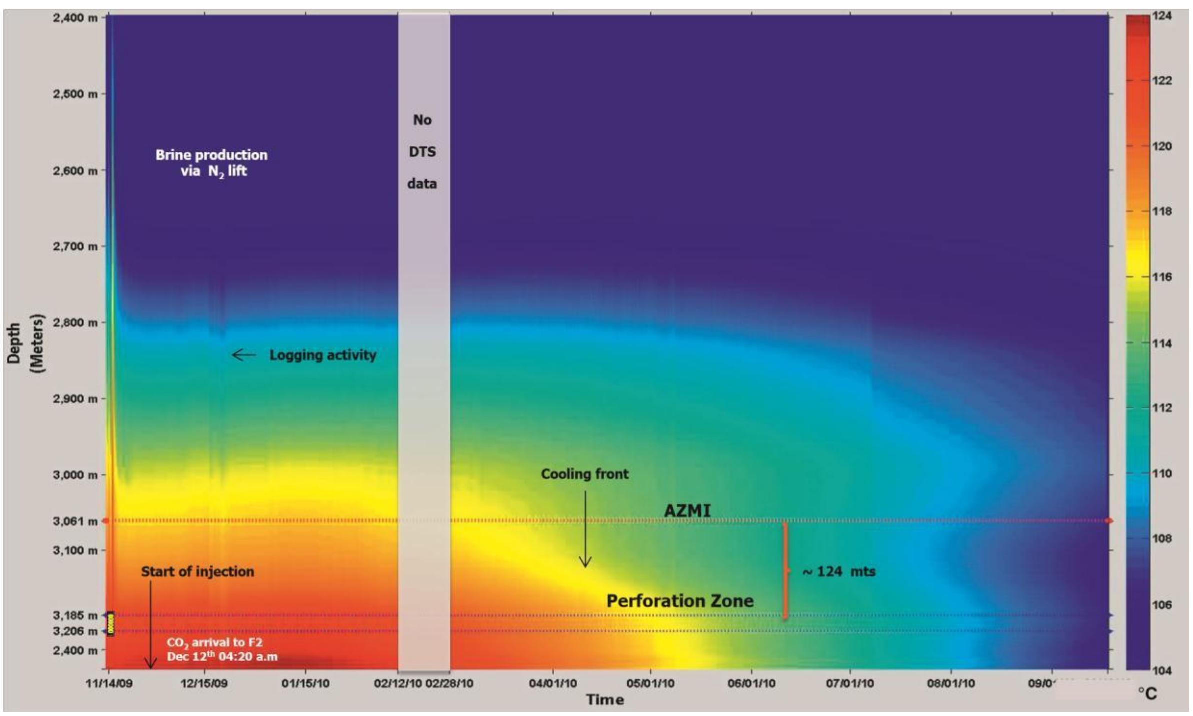


Figure 26 . At observation well F2, Temperature Variation, vertical distribution, and timing of temperature evolution from Nov. 14th 2009 to September 18th 2010 [1].

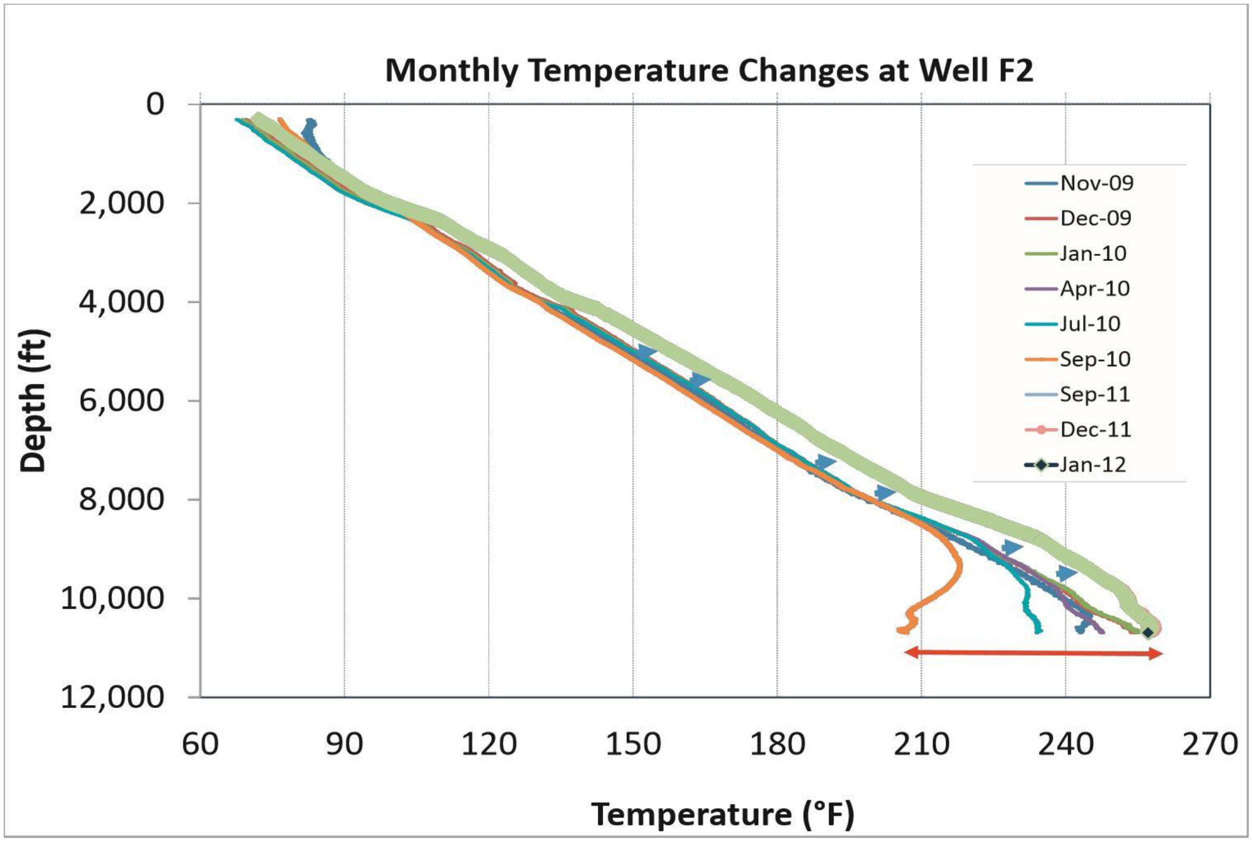


Figure 27. Monthly temperature gradient evolution of F2 well [1].

Combination of the DTS data and pressure monitoring and imaging technologies can give valuable information. The main pros of the DTS over the conventional temperature guage is of the availbility of the data along the length of the well. But gauge reading is much more stable. The reading of the DTS is affected by the noise at deep depth of the well. The standard deflection of temperature is over half a degree F at the bottom of the F3 well. This analysis is important when analyzing the sensitivity of the tool for monitoring the leak and ranges of application in well completion. The measurement of DTS is unstable at deeper depth of 3000m becasue of the instrumental drift.

4.3 Analysis of Distributed Acoustic Sensing

4.3.1Challenges and Limitations of Distributed Acoustic Sensing in Geophysics

Apart from DAS advantages over Geophones, there are various limitation, weakness and challenges which still limits its applications.

- **Low Signal to Noise Ratio (S/N)**

The data obtained from Distributed Acoustic Sensing (DAS) is much noisier as compared to the data acquired from Geophones. The interrogator Unit generates the DAS noise which are random noise, on all receivers the time variant optical noise and spike like noise that occur equally [54]. These random noises sometimes overlap the weak signals which make it difficult to detect in microseisms application. The impact of noise can be reduced by stacking the data obtained from various fibers and by applying noise removing technique [55]. Figure [28] shows the comparison between DAS and Geophone S/N ratio for different windows.

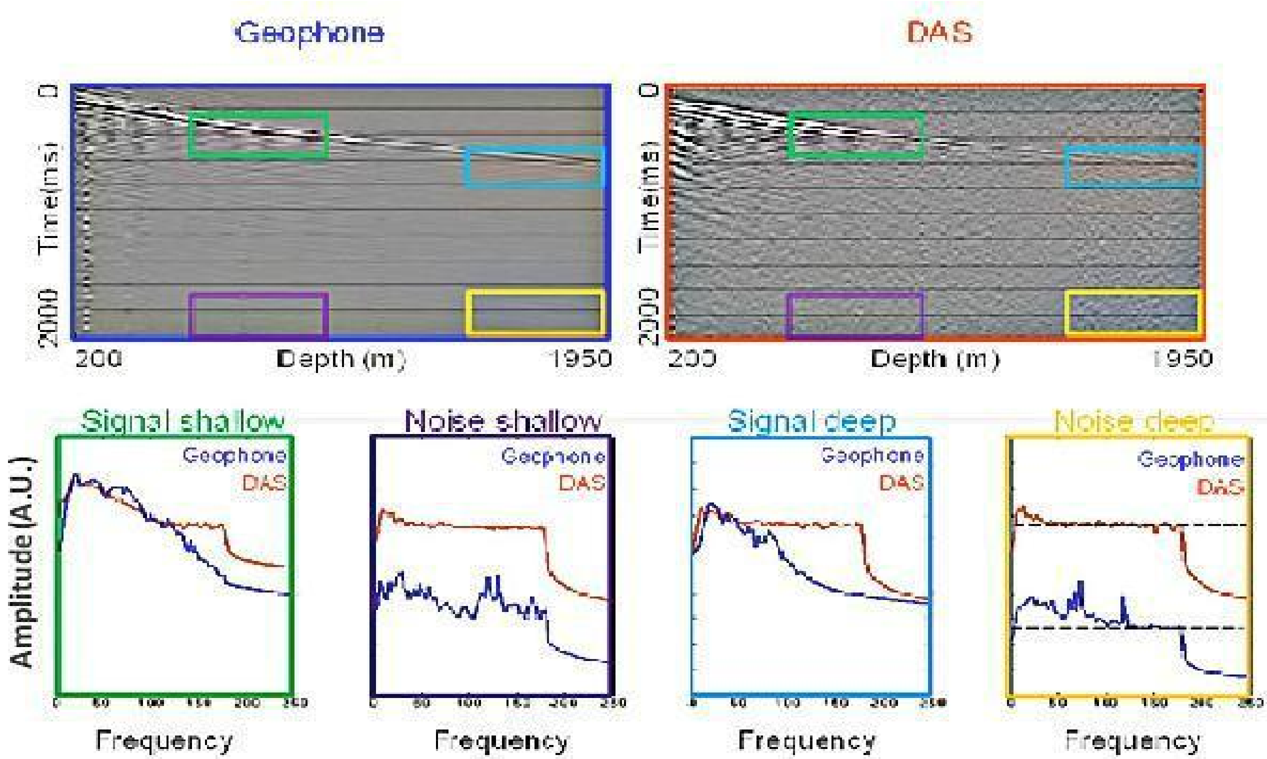


Figure. 28 Geophones vs DAS Data

- **Depth Uncertainty**

In depth the position of DAS channels is located by the back scattered light. In downhole application the length of fiber varies due some many factors. For example, due to gravity the fiber may bended in horizontal well which cause the fiber may stretched by itself; and to protect snapping the fiber may be longer than the measured depth when descending along the well with the cable, etc. All these reasons and factors causes the uncertainty of position which leads to the interpretation of the seismic data with errors. In time lapse Distributed Acoustic Sensing vertical seismic profile applications this is an important limitation. And to compare (NDRMS) Normalized Difference in Root Mean Square of the observation of different time the depth of receiver must be accurate.

- **Poor transverse Fiber Sensitivity**

Distributed Acoustic Sensing measure only strain along the optical fiber but the stains transvers to the cable can be recorded very hardly. This means that Distributed Acoustic Sensing (DAS) is more sensitive to P waves as compared to S waves. So, in near-offset DAS micro-seismicity, DAS VSP the information related to the S-waves may be absent, only shear waves are dominant which are related to the induced fractures in Hydraulic Fracturing process [29]. The 1-C geophones are not sensitive to transverse sensibility whereas the DAS is more sensible, which can be shown in Figure (29)

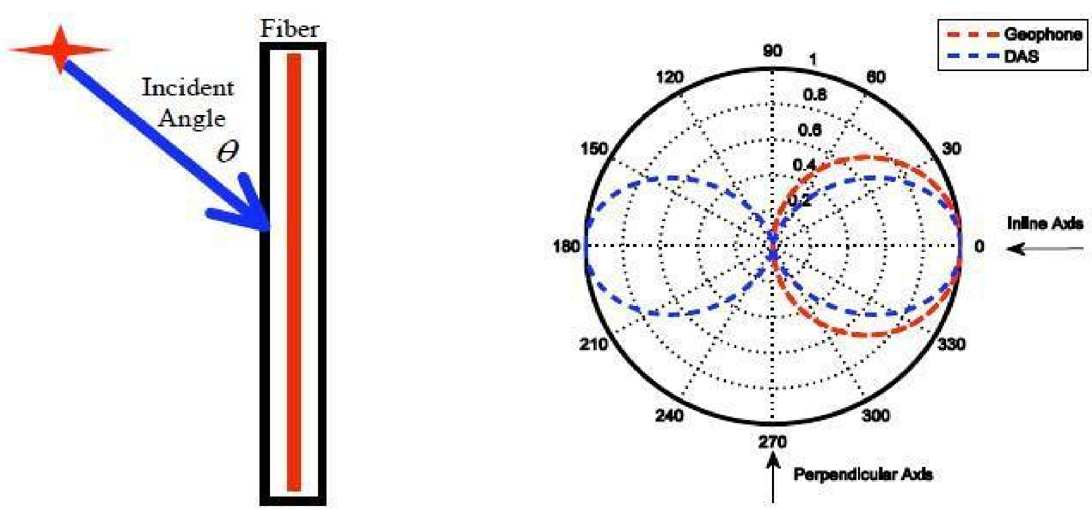


Figure: 29 Approximate amplitude-incident angle plots of DAS (blue) and geophone (red)

For Distributed Acoustic Sensing (DAS) the sensibility of the transverse is $(\cos \theta)^2$ whereas in geophones it is near to the $(\cos \theta)$ [58]. The amplitude and the P waves depends on the incident angle in DAS, when it is zero along the inline axis these factors become maximum. Where as in case of deviation of the incident angle from zero the P waves and amplitude decreases abruptly as compare to in Geophone.

In DAS micro seismicity and DAS VSP this limitation is very serious. The information related to the S-waves usually absent in near offset VSP applications because shear waves are perpendicular to the fiber and DAS can only be sensitive to strains. In most of the cases the shear waves are related to the induced fractures while missing of the shear waves could be the result of misinterpretation of hydraulic fracturing [30].

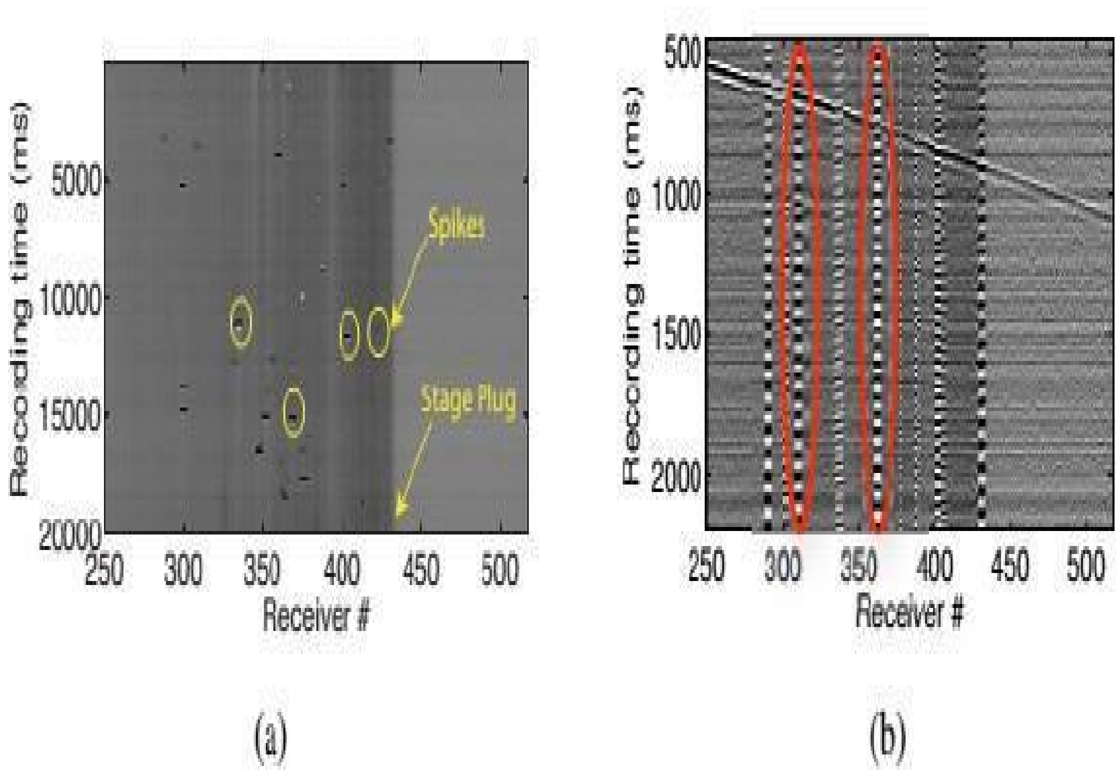


Figure: 30 a) Raw DATA b) Correlated Data

In micro seismic application when the source is closer to the near well bore hole the S waves energy travel or propagate perpendicular to the axis of the borehole so in DAS measurement it don't appear but when the source is far from the wellbore then the energy of the P waves reduced too so in this case DAS measurement are poor of many real time data especially of real location of the source.

- **Deployment of the Cable in Harsh Environment**

The optical fibers deployment is neither expensive nor complex, but the installation of the Interrogator Unit (IU) is very hard in extreme environment like subsea, jungles and deserts. And because of the influence of the storm, ocean and sunlight the quality of the signals recorded by the permanent IU often degraded. Therefore, the material of IU must be of better quality for surviving harsh environment. And the installation cost of IU should be low as the DAS technology are in extensive use.

4.3.2 Methods for Lessening the Limitations of DAS

- **Removal of Noise**

The in-practice techniques for removing noise are median filter, band-pass filter and stacking of multiple fiber measurements. The main purpose of these technique is for removing noise which are time variant and due to the fluctuation in temperature downhole and optical noise [60, 61]. Apart from the background noises in DAS VSP measurement spike noises appear to be more prominent and dominant in DAS data [60]. Figure (30) shows a DAS VSP measurement with vibroseis source during hydraulic fracture simulation. The presences of horizontal spikes like noise on both data (a) Raw Data (b) Correlated Data. Moreover, on correlated data the vertical spikes noise also appears above the plug of receiver number 432. These vertical spike noise is related to the spike like noise and display in time domain after matching with vibroseis source signal. As compared to the background noise the amplitude of the spike noise is much bigger and are easily remove from the traces by the application of the amplitude threshold. In every waveform with higher amplitude greater than the threshold amplitude are set zero.

The threshold amplitude is obtained by taking the product of the median amplitude of all sample point in traces and the scale factor equation (vii)

$$Threshold = \alpha_i . \frac{\sum_{j=1}^{T} Amp_i^j}{T}, i = 1:N$$

Where,

Threshold = Refers to the amplitude threshold

= Refers to the scale factor

= Refers for to the amplitude of ith trace

T = is the total time sample number

N= is the total number of traces

This processing technique of the threshold is performed to each trace and for further improving the S/N ratio the median filter is employed. Figure [31] shows the comparison among,

(a) Pre-Stimulation Stacked Correlated Signal
(b) Post-Stimulation
(c) Pre-Stimulation stacked correlated signal before removing noise
(d) After removing noise

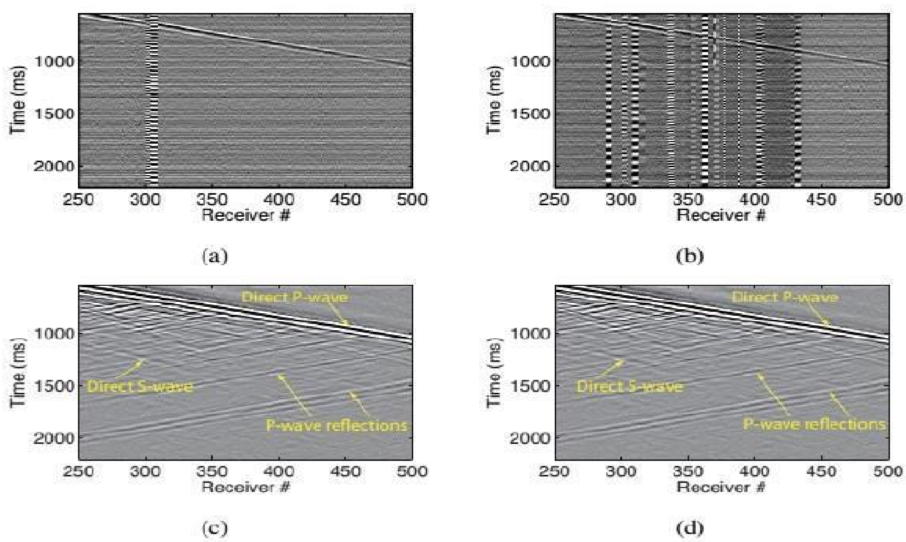


Figure: 31 stacked correlated signal pre-stimulation (**a**) and post-stimulation (**b**) before noise removal and stacked correlated signal pre-stimulation (**c**) and post-stimulation (**d**) after noise removal

- **Depth Calibration**

Calibration of the depth is another very critical issue in DAS measurement in application related to time-lapse. There are two methods for calibrating the DAS channel depth.

(a) Tube wave reflections
(b) DC level

Along the axis of the borehole the ***tube waves*** travel with the linear move out in the liquid saturated well. In each steps of the hydraulic fracturing from the perforation shot the tube wave generated and are used to identify the plug position. The plug location is identified in the trace with the reflection interface of the tube waves. Now after comparing the plug location identified by the tube waves and the real plug location, the exact location of the DAS channel can be determined.

Direct Current level is considered zero in ideal situation basically it is the average amplitude of each trace. With the variation of the temperature in the borehole. Direct current level above the lowest perforation position is negative and it jumps to zero right below the lowest perforation location. By this negative and zero inflection of the DC level curve the location of the plug can easily be detected.

Figure [5]. Shows the (a) the Tube Waves Reflection and (b) DC level jump for locating the DAS channels. And it is observed that the tube waves are reflected at the receiver number 432 which is supposed to be the plug location. By this way, the depth of the receiver is determined after comparing the actual receiver depth. And in the same way the depth of the other receiver can be determined. In the same way, the DC curve towards negative value represent the depth above the plug and towards zero inflection corresponds below of the plug.

Chapter # 5

Conclusion

The measuring technique of the Temperature, Pressure and Strain for downhole monitoring was developed in 1930s and with the passage of time for better accuracy and resolution new sensors were developed and among them all Fiber Optical sensors are very much effective.

- **Issues and Future Directions for FBGs**

For oil and gas Industry especially, its application in health monitoring of pipeline and well logging Fiber Bragg Grating is a permissive technology. FBGs offers great measuring data on different sensitive parameter like temperature, strain and pressure, vibration in harsh environments. Monitoring by online in oil and gas application is possible by FBGs. There are plenty of research and development area in FBGs technique.

- Long distance downhole cable
- Configuration and Design of Sensors
- Packaging and Adequate fiber coating
- Fiber interfaces/host material Mechanics
- High performance FBGs and New sensing fiber

Now moreover the promotion of fiber optical sensor on industrial scale is necessary because of its accuracy in oil and gas well logging, monitoring of health issues of pipeline and seismic exploration.

- **Distributed Temperature Sensors (DTS)**

Most important information and data can be extract from DTS data, when combining with pressure data. The main difference between temperature gauge and the DTS is of the continuous distributed temperature monitoring by DTS. But readings of the temperature gauges are more stable as compared to DTS. In DTS the data accuracy at certain deep depth is affected by noise factor as noise is proportional to the depth. And the deviation of the DTS is 0.5 F at the depth more than 3000 meters. The consideration of this deviation is important when taking a reading of leaks at high depth. The reason of this inclined in measurement is the instrumental drift.

- **Future Direction**

More comprehensive sensitivity analysis in future to minimize the instrumental drift and sharp warming at high depth

Numerical modeling and simulation is needed for other factors which play an important role on the temperature change traveling speed.

- **Distributed Acoustic Sensors (DAS)**

Distributed Acoustic Sensing is the most promising tech in petroleum industry but there is still future work needed to be done. Improvement on Signal to noise ratio (S/N) is very important area of DAS. The solution of how to improve it is by

- The application and choice of powerful acoustic source like Multiple vibrators.
- And by stacking signals of other optical fiber sensors

By correlation and coherent stacking, the S/N can be improved.

Second, problem is the Interrogation of the accurate receiver channels in deep depth.

Solution

- Utilization of the check-shots for the calibration of the receiver channels in deep depth.
- Application of DC bias and Tube wave reflections for application in borehole.

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