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A REVIEW OF DISTRIBUTED FIBER OPTICS TEMPERATURE SENSING: APPLICATIONS, CHALLENGES & FUTURE RESEARCH OPPORTUNITIES

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Abstract

In recent years, the Distributed Fiber Optics Temperature Sensing (DTS) technology has gained wide acceptance in various fields of science and technology. These includes Atmospheric Science, Hydrological Science, Geological Science, Oceanography, and several fields of Engineering. However, despite this wide acceptance, not many articles have been written on the theory, applications, and challenges of the Distributed Fiber Optics Temperature Sensing (DTS) technology in the aforementioned fields. Therefore, the objective of this paper is to present a comprehensive review of the theory and applications of the Distributed Fiber Optics Temperature Sensing (DTS) technology in Engineering, Oceanography, Atmospheric Science, Hydrology, and Geological Science. In this study, we investigated the potentials of Distributed Temperature Sensing (DTS) in Oceanography and Atmospheric Science, fields often neglected by authors who had previously written articles on the subject of Distributed Temperature Sensing (DTS). Additionally, we also discussed some challenges facing the deployment of the DTS technology in Hydrology, Oceanography, and Atmospheric Science. Finally, we also outlined some opportunities for future research on the applications of Distributed Temperature Sensing (DTS) in Oil & Gas, Hydrology, Geological Science, Oceanography, and Atmospheric Science. This study shows that Distributed Temperature Sensing (DTS) has great potentials in the aforementioned fields if the challenges outlined in this paper are properly addressed through cutting-edge research.

Keywords: Distributed Temperature Sensing; Applications; Challenges; Research Opportunities.

1.0 Introduction

Distributed Temperature Sensing (DTS) is a technique that can be used for continuous measurement of temperature values along an optical fiber cable at every point in time. It is a means of quantifying the spatial and temporal variation of temperature across a fiber cable. The process involves passing a laser of light through the core of an optical fiber cable. As the laser of light travels through the optical fiber cable, the pulse of light collides with the internal lattice structure, as well as the atoms of the optical fiber cable. This causes them to emit some bursts of light at slightly different frequencies which travel back in opposite direction towards the top of the optical fiber cable. The “backscattered” light is then examined by the instrumentation box to obtain an estimate of the temperature at the point where the backscatter light originated. As the velocity of light in the medium is constant, the two-way travel time of the laser light pulse can be used to determine the actual location of the recorded temperature along the fiber.

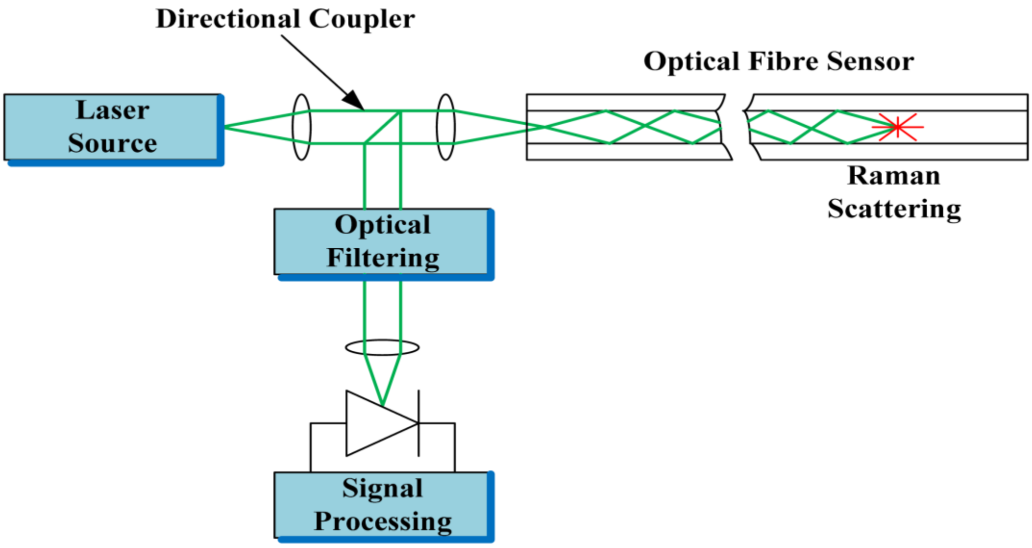


Fig 1: A typical DTS system setup [1]

A continuous profile of the temperature along the fibre cable is obtained from continuous measurement of the backscattered light. This temperature profile is known as Distributed Temperature Survey (DTS).

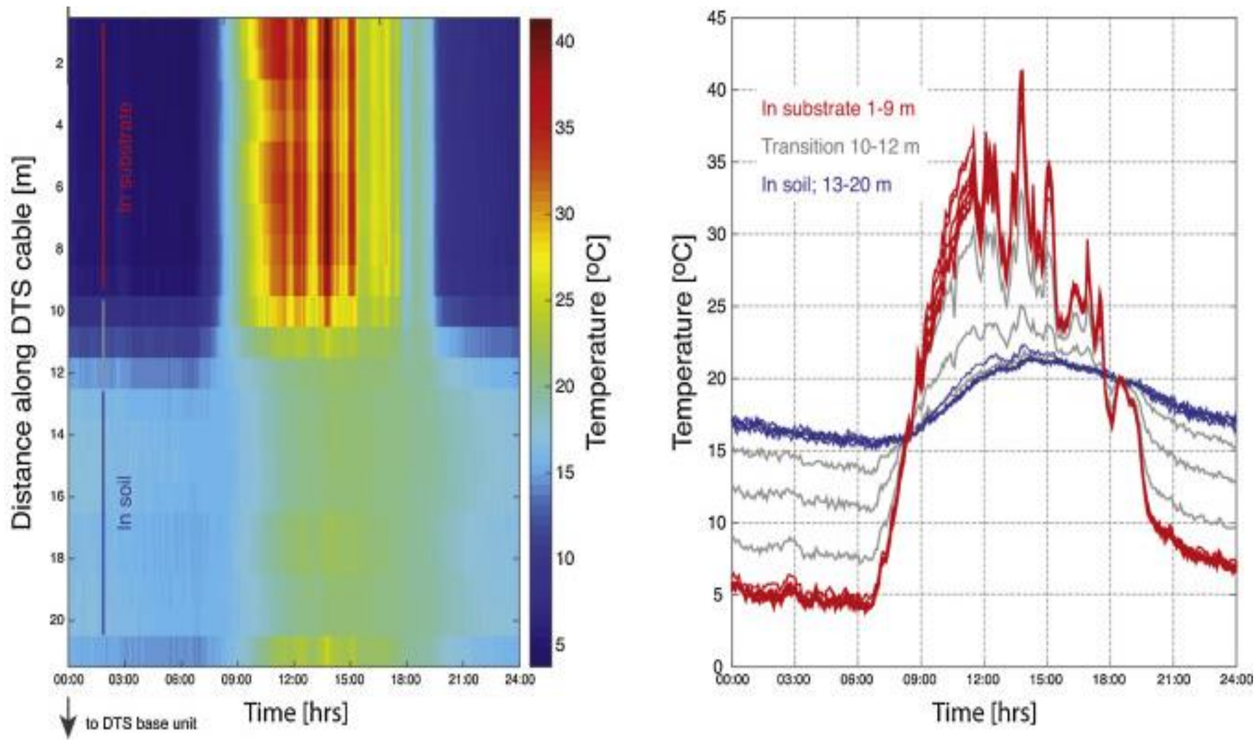


Fig 2: Distributed Temperature Survey (DTS) Showing Both Spatial and Temporal Temperature Distribution Along the Fiber [2]

The main backscattered light is called the Rayleigh wave and it is at the wavelength of the launched light. The Rayleigh wave is by far the strongest signal recorded by the instrumentation box. However, this Rayleigh signal is usually filtered out, except in some cases. The retuned backscattered waves associated with the lattice vibrations are known as Brillouin waves. The Brillouin waves are similar to and often difficult to distinguish from the Rayleigh waves. Finally, Raman waves are the weakest of the backscattered waves. They result from molecular and atomic vibrations. The Raman signals are sensitive to temperature and are used for temperature evaluation across the length of the fiber cable. The Raman signals consist of two different bands: Stokes & anti-Stokes. The Stokes band has a higher wavelength. It is also stable and therefore has little temperature sensitivity. Conversely, the anti-Stokes band has lower wavelength, less stable, and has a higher temperature sensitivity.

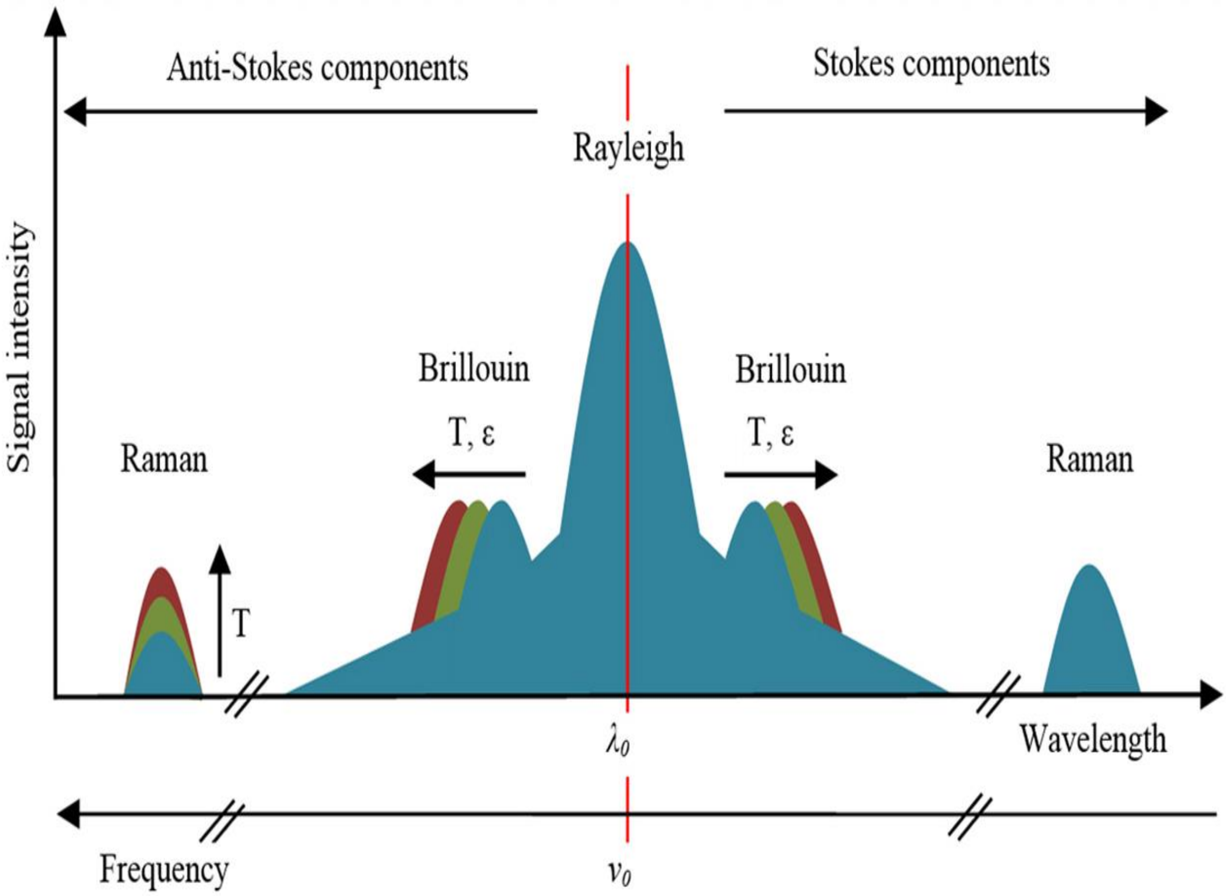
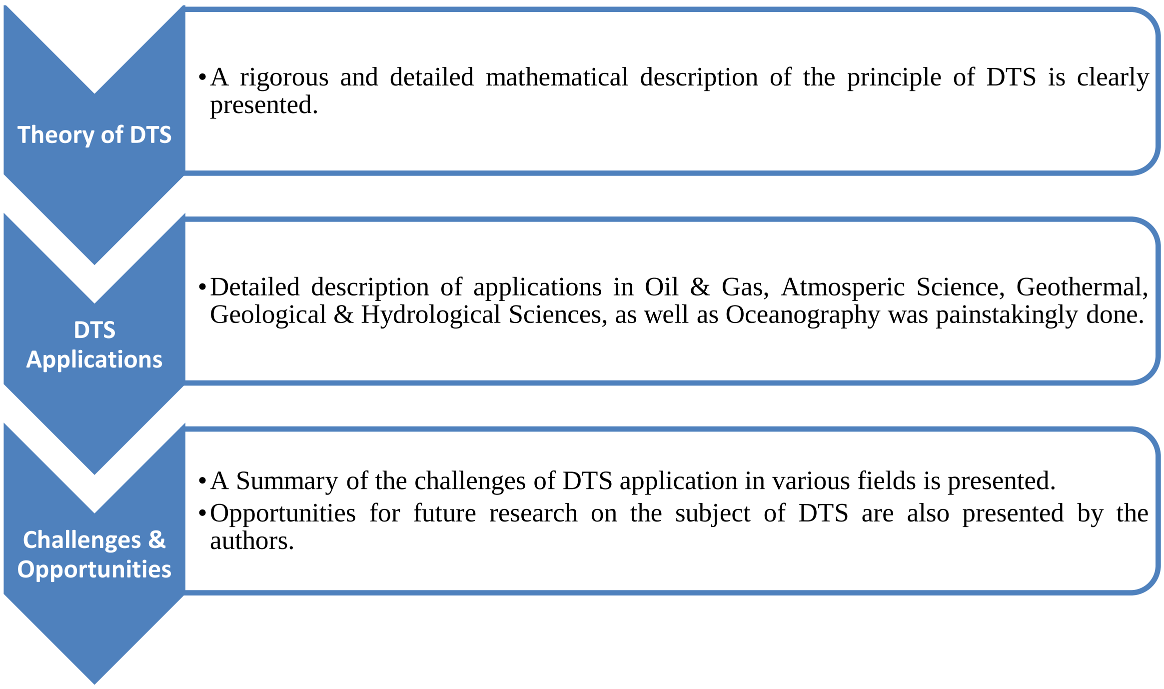


Fig 3: Spectrum of the back-scattered light during DTS [25]

The ratio of the energy of the Anti-Stokes band to that of the Stokes band can be easily related to the temperature of the fiber optic cable at the depth where the back-scattered signal originated.

2.0 Methodology/Workflow

The flow chart below gives a description of the workflow employed in this study. It describes the activities carried out in a sequential manner.



2.1 Theory of Distributed Temperature Sensing

As the laser pulse travels through the fiber, its intensity decreases exponentially with depth. The equation below describes the variation of the intensity of the propagating laser pulse with depth.

$$\mathbf{I(z) = I_0 e^{-\alpha Z}} \qquad (1)$$

Where $I(z)$=Intensity of the laser pulse at depth, z

I_0 = Initial intensity of the laser pulse

α = Attenuation coefficient and it is a property of the fiber

The Intensities of the back-scattered stokes and anti-stokes Raman waves are also by some parameters. The equations presented below describe the relationship between the intensities of the back-scattered waves and the parameters affecting them.

$$\mathbf{I_+(z) = C_+ e^{-\alpha_R Z} e^{-\alpha_+ Z} \langle n_k \rangle} \qquad (2)$$

$$\mathbf{I_-(z) = C_- e^{-\alpha_R Z} e^{-\alpha_- Z} \left(\langle n_k \rangle + 1 \right)} \qquad (3)$$

Where;

$$\langle \mathbf{n_k} \rangle = \frac{\mathbf{e}^{-\frac{\hbar\Omega}{KT(z)}}}{1-\mathbf{e}^{-\frac{\hbar\Omega}{KT(z)}}}$$

$$\hbar = \frac{\mathbf{h}}{2\Pi}$$

h = Planck Constant

K = Boltzmann Constant

$2\Pi\Omega$ = Frequency

C_+ and C_- are constants

Equations (2) and (3) above give quantitative description of the intensity of the back-scattered Raman waves in the stokes and anti-stokes region respectively.

Since the DTS measurements depends on the ratio of these two intensities, we can therefore take the ratio of the above equation.

If we take the ratio of the above equations, we obtain the following result

.

$$\frac{I_+(z)}{I_-(z)} = \frac{C_+}{C_-} e^{-\Delta\alpha Z} e^{-\frac{\hbar\Omega}{KT(z)}} \quad (4)$$

Equation (4) above is the ratio of the intensity of the back-scattered Raman waves in the stokes region to that of the anti-stokes region.

Solving for temperature in the above equation, we obtain the following result.

$$T(z) = \frac{\frac{\hbar\Omega}{K}}{\ln\left(\frac{C_+}{C_-}\right) - \ln\left(\frac{I_+(z)}{I_-(z)}\right) - \Delta\alpha Z} \quad (5)$$

The above equation gives the magnitude of the temperature at different position along the fiber.

The equation can be simplified further by obtaining its power series approximation. Applying power series expansion to the equation and truncating the resulting expression after the second term, the result below is obtained.

$$T(z) = \frac{\frac{\hbar\Omega}{K}}{\ln\left(\frac{C_+}{C_-}\right) - \ln\left(\frac{I_+(z)}{I_-(z)}\right)} \left[1 + \frac{\Delta\alpha Z}{\ln\left(\frac{C_+}{C_-}\right) - \ln\left(\frac{I_+(z)}{I_-(z)}\right)}\right] \quad (6)$$

Further simplification by applying the power series approximation two more times produces the following result.

$$T(z) = \frac{\hbar\Omega}{K \ln\left(\frac{C_+}{C_-}\right)} \left[1 + \frac{\Delta\alpha Z}{\ln\left(\frac{C_+}{C_-}\right)} + \frac{\ln\left(\frac{I_+(z)}{I_-(z)}\right)}{\ln\left(\frac{C_+}{C_-}\right)} + \cdots\right] \quad (7)$$

The above equation can be reduced further to the following form.

$$T(z) = T_{ref} \left[1 + \frac{\Delta\alpha Z}{\ln\left(\frac{C_+}{C_-}\right)} + \frac{\ln\left(\frac{I_+(z)}{I_-(z)}\right)}{\ln\left(\frac{C_+}{C_-}\right)}\right] \quad (8)$$

Where T_{ref} is the reference or baseline temperature.

It evident from the result above that DTS temperature measurement depends strongly on the reference temperature, depth, and the ratio of the intensities of the back-scattered Raman waves in the stokes and anti-stokes regions.

Furthermore, we can describe mathematically, the effects of depth on temperature resolution by calculating the standard deviation of the temperature as follows;

$$[\Delta \mathbf{T(z)}]^2 = \left\{\frac{\partial \mathbf{T}\left(\frac{I_+(z)}{I_-(z)}\right)}{\partial\left(\frac{I_+(z)}{I_-(z)}\right)}\right\}^2 \left(\left(\frac{I_+(z)}{I_-(z)}\right)\right)^2 = \left\{\frac{\partial \mathbf{T}\left(\frac{I_+(z)}{I_-(z)}\right)}{\partial \ln\left(\frac{I_+(z)}{I_-(z)}\right)} \frac{\partial \ln\left(\frac{I_+(z)}{I_-(z)}\right)}{\partial\left(\frac{I_+(z)}{I_-(z)}\right)}\right\}^2 \left(\Delta\left(\frac{I_+(z)}{I_-(z)}\right)\right)^2$$

Simplifying the above expression, we have;

$$[\Delta \mathbf{T(z)}]^2 = \left\{\frac{1}{\left(\frac{I_+(z)}{I_-(z)}\right)} \frac{\partial \mathbf{T}\left(\frac{I_+(z)}{I_-(z)}\right)}{\partial\left(\frac{I_+(z)}{I_-(z)}\right)}\right\}^2 \left(\Delta\left(\frac{I_+(z)}{I_-(z)}\right)\right)^2$$

$$\frac{\Delta \mathbf{T(z)}}{\mathbf{T(z)}} = \frac{\mathbf{T(z)}}{\frac{\hbar\Omega}{K}} \left\{\frac{\Delta\left(\frac{I_+(z)}{I_-(z)}\right)}{\left(\frac{I_+(z)}{I_-(z)}\right)}\right\} \qquad (9)$$

Substituting equation (4) into equation (9), we have;

$$\frac{\Delta \mathbf{T(z)}}{\mathbf{T(z)}} = \left(\frac{C_-}{C_+}\right) \frac{\mathbf{T(z)}}{\frac{\hbar\Omega}{K}} \ \mathbf{e}^{\Delta\alpha \mathbf{Z}} \ \mathbf{e}^{\frac{\hbar\Omega}{KT(z)}} \Delta\left(\frac{I_+(z)}{I_-(z)}\right) \qquad (10)$$

The above equation shows that the standard deviation of the temperature increases exponentially with depth.

2.2 DTS Applications

2.2.1 Oil & Gas Industry

In recent years, the DTS technology has gained wide acceptance in several fields of science and technology. In the last decade, the oil and gas industry has deployed the technology the most to proffer solutions to some long-standing challenges. Fortunately, the technology has proved effective so far in overcoming some technical challenges facing the industry. [6]**,** demonstrated the suitability of hybrid DAS-DTS for estimating the pressure profile of a well at different gas injection volume, backpressure, injection methods, and water circulation rates. They also applied the technology to monitor the injection profile of a well. Research had also been done to demonstrate the potential of DTS for flow profiling in reservoirs and borehole [16]**,** [7]**,** [10]**,** [27]**,** [21]**,** [24]**.**

Fig 4: DTS being installed for Production and Injection Monitoring at Louisiana State University PERT Laboratory [2]

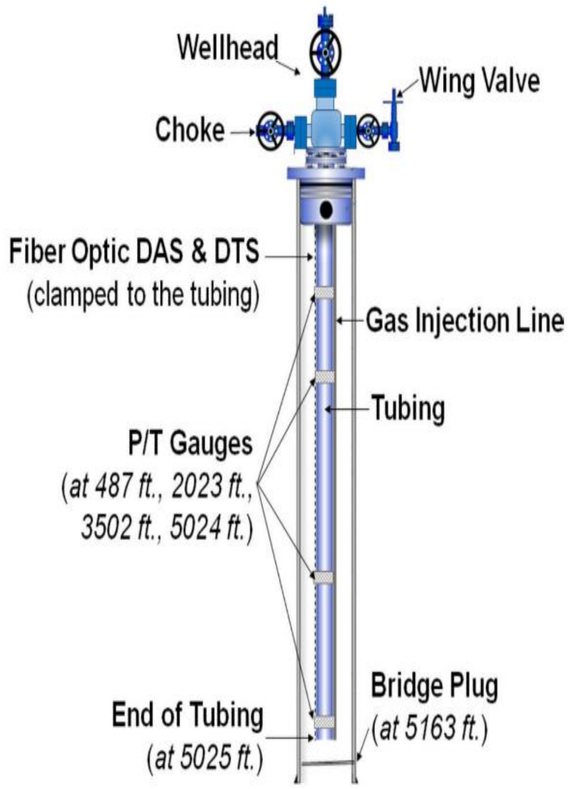


Fig 5: Schematic diagram of a well under investigation using DTS at Louisiana State University PERT Laboratory [25]

[31], in a thesis submitted to Stanford University, discussed, and demonstrated the applicability of DTS in building a wellbore/reservoir coupled thermal model, estimating flowrate profile, and evaluating formation properties. This demonstration was carried out on vertical, deviated, and horizontal wells.

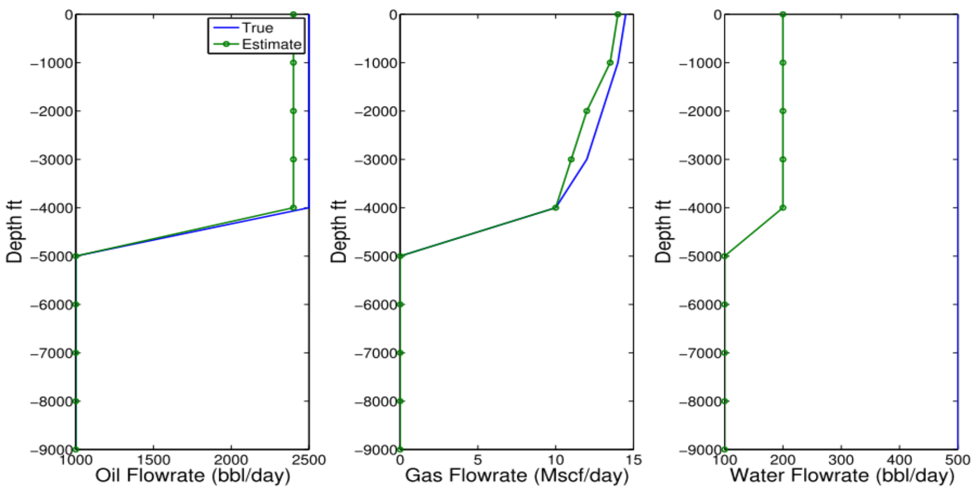


Fig 6: Flow rate estimation in a multiphase system using DTS [31]

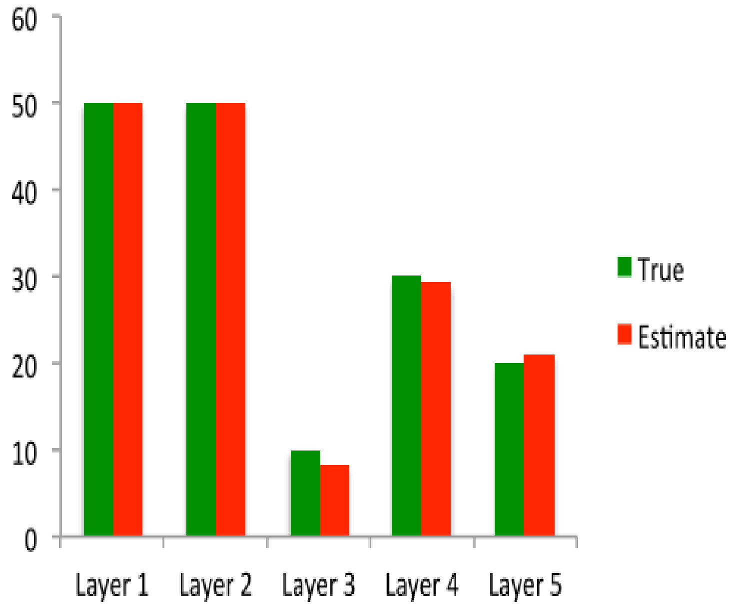


Fig 7: Estimation of the permeability of a multi-layered reservoir system using DTS [31]

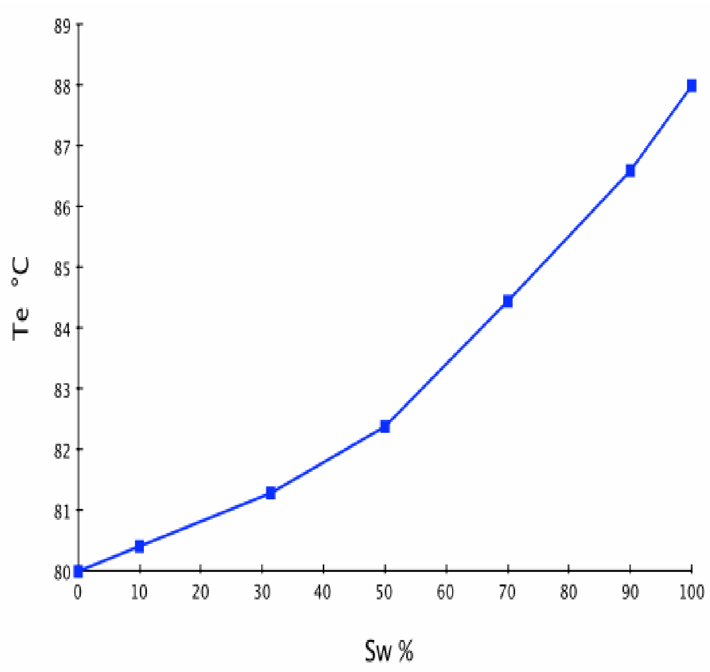


Fig 8: Relationship between DTS temperature and reservoir water saturation [2]

DTS has also been deployed in a producing oil well to detect multiple leakages. The technology proved effective as multiple leakages were discovered in limited time [5]. In a similar vein, [29], published a comparative review of the DTS, they also highlighted some of its applications in the oil and gas, leakage detection, fire detection, and mines. In addition, [30],discussed the basic principles of DTS with more emphasis on its applications in the oil and gas industry. They also discussed its interpretation, quality control, and the uses of DTS data.

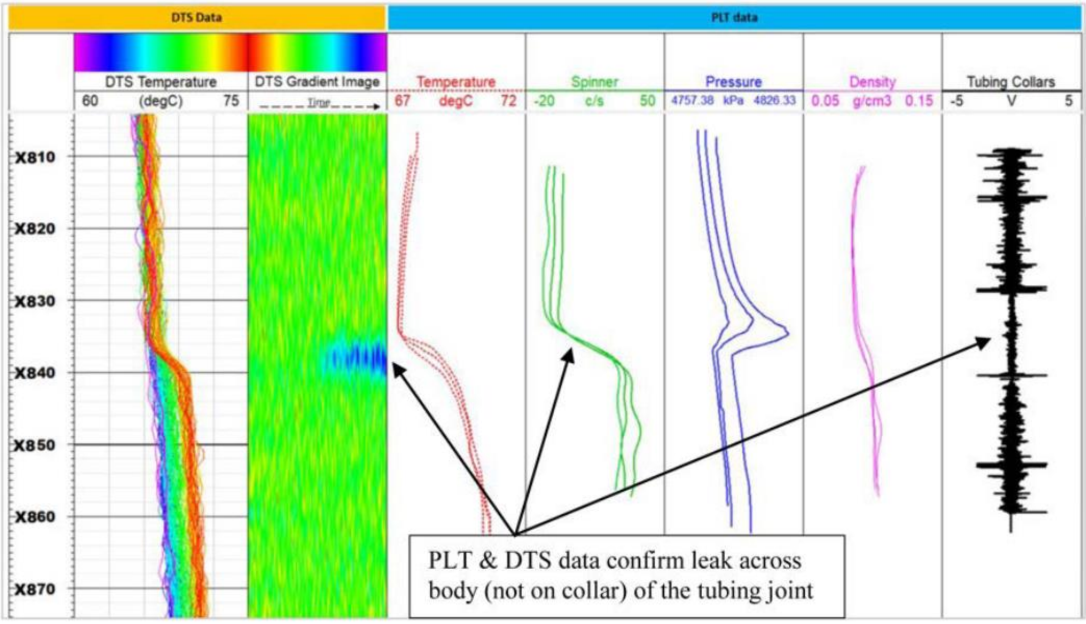


Fig 9: Illustration of DTS application in leak detection [5]

2.2.2 Atmospheric Science

Research has been done on the potential of DTS application in atmospheric science. [4], employed DTS to measure atmospheric air temperature. They also proposed an approach to correct for the effects of solar radiation on atmospheric DTS applications. Satisfactory results were obtained from their experiment. Similarly, [15], studied the suitability of DTS for evaluating and analysing atmospheric mixing profiles in a tropical environment.

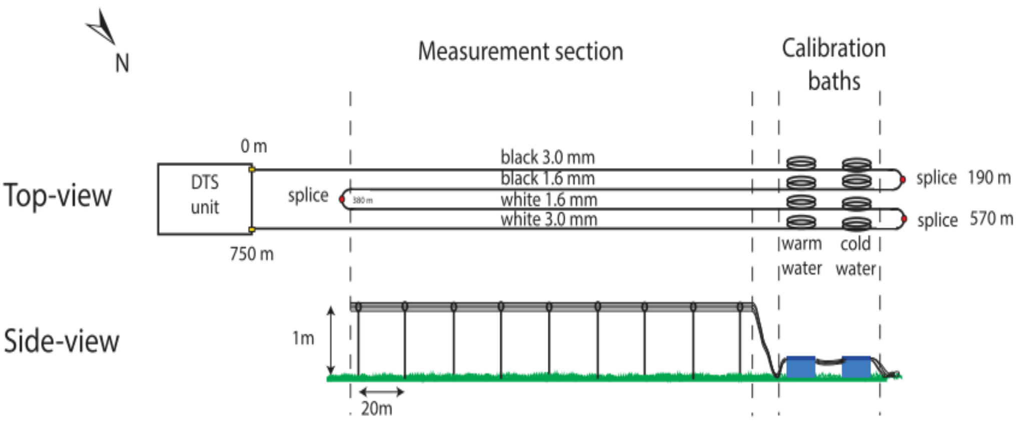


Fig 10: Experimental setup for atmospheric air temperature determination using DTS [4]

[32], also employed the DTS to determine the spatial and temporal variations in snow temperature in California, USA. Their results did demonstrate the suitability of the DTS for this purpose. However, the absolute snow temperature could not be obtained due to some errors introduced through temperature stratification in the calibration section.

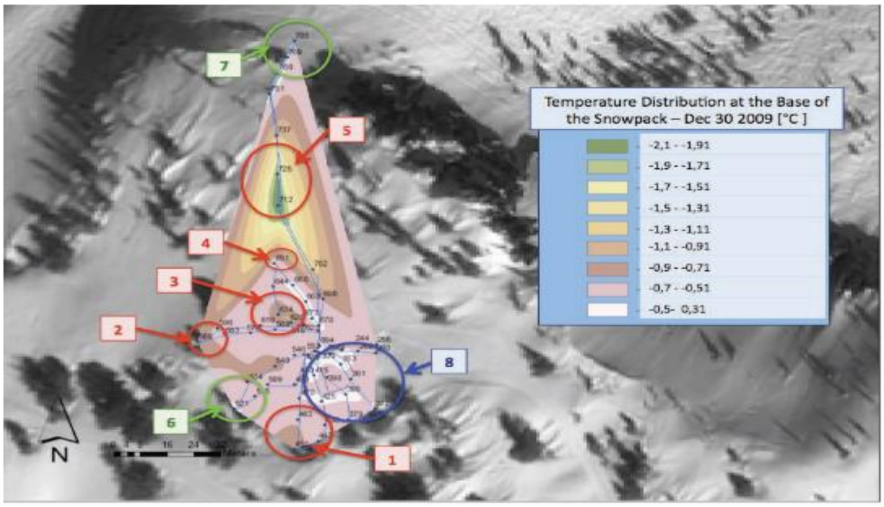


Fig 11: Temperature distribution in California obtained using DTS [32]

Furthermore, a novel fiber optics laser had also been developed with the aim of overcoming the pressure effects at high atmospheric altitudes. The results obtained using this novel fiber showed reasonable agreement with observed meteorological data [9].

2.2.3 Geological Science

The DTS technology has also been embraced to great effect in geological science. [11], introduced an autonomous DTS that is deployable for long-term temperature profile measurement in remote areas. They established that the developed autonomous system has a potential to overcome some of the barriers to DTS applications in geological science. Also, [28], deployed the DTS to monitor the stability of the Antarctic ice. The results of the research show that DTS has great prospect for achieving a higher spatial temperature sampling than other conventional techniques being employed. Although their work was limited by two challenges: Ice penetration and inability to achieve long term operation for non-recoverable sensors, they clearly demonstrated the potential of DTS in this field.

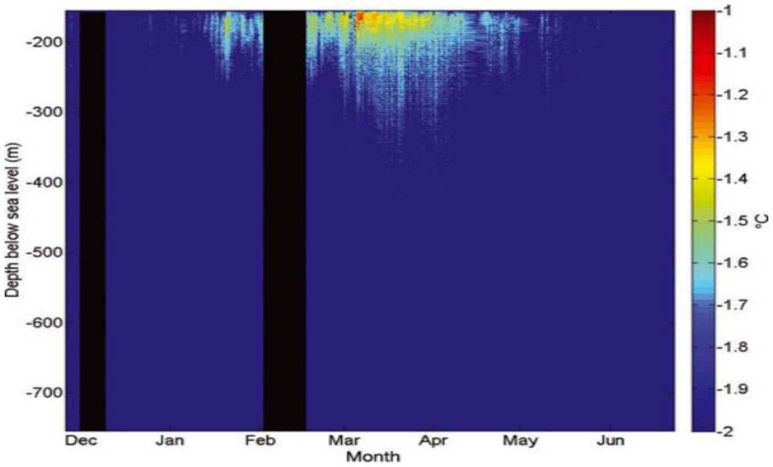


Fig 12: Study of Ocean Temperature Dynamics using DTS [28]

Besides, [19] also carried out an experimental and numerical study to monitor variations in sediment overburden using DTS. They developed a correlation between temperature and sediment thickness. Although their experiment could only be conducted on a small scale, the potential of conducting such experiment on a field scale offers opportunity for further study.

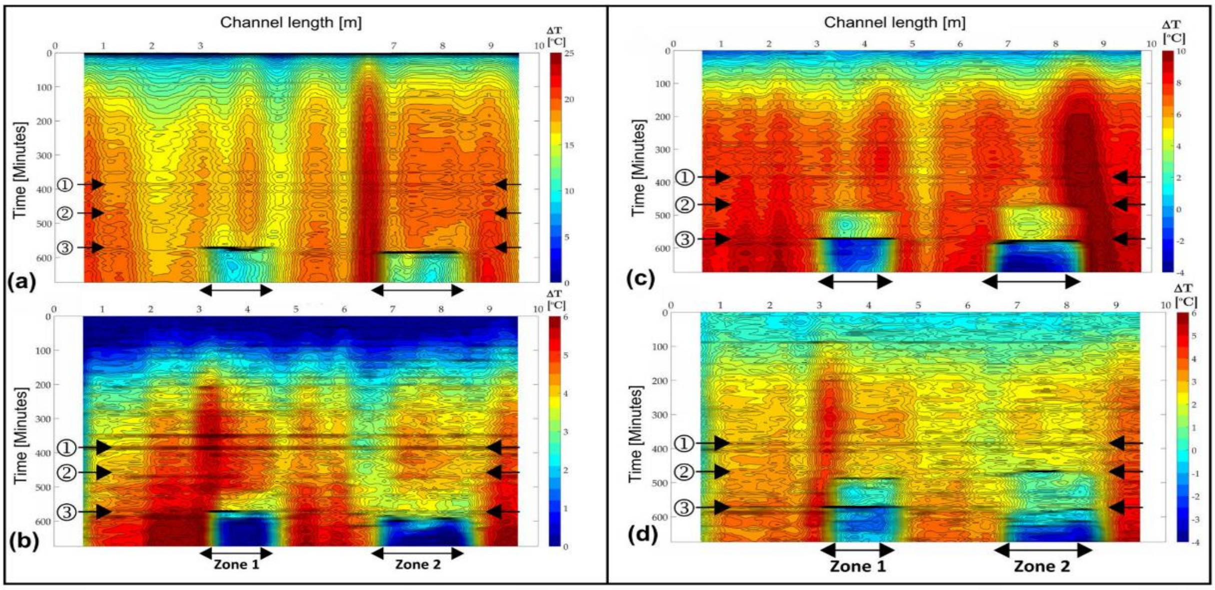


Fig 13: DTS Temperature Contours Illustrating Changes in Overburden [19]

Furthermore, [12] proposed a novel temperature demodulation with difference method in an attempt to improve the accuracy of the DTS results in geological sciences. Their result shows a significant improvement in accuracy. Finally, they suggested that the accuracy of the system can be improved further by employing advanced coding and denoising techniques. In like manner, [8] evaluated the prospect of DTS in seepage detection and monitoring. They also discussed different calibration and interpretation techniques for DTS measurements.

2.2.4 Hydrological Science

hydrological science hasn't been left out. In recent year, DTS has also gained relevance in hydrologic science. [22], deployed DTS to monitor the temperature distribution along a first-order stream, determine temperature profile at the air-snow interface, as well as air-water interface. The validity of the results obtained over a short time was greatly hampered by precision, temporal resolution, and spatial resolution. Consequently, they were able to obtain appreciable results only after a long span in time and space. Similarly,[3], in their study on hyporheic flow, they investigated the potential of DTS in quantifying variabilities (spatial & temporal) in vertical hyporheic flow. They also deployed a robust DTS in Wyoming stream and data was collected continuously for a period of thirty days. The DTS data obtained was then combined with some analytical techniques to gain insight into the spatial & temporal variabilities of the flow. Furthermore, [18], Investigated the limitation of DTS in monitoring surface water and groundwater interaction. They developed a correlation between temperature and ground water discharge. Finally, they observed that the reliability of the DTS for this purpose was somehow limited by surface water and groundwater velocities. Moreover, [25], Outlined the applications and limitation of DTS for subsurface investigation of hydrogeological processes. They concluded that DTS has significant advantages over other method being employed in the field of hydrogeology to investigate subsurface hydrogeological processes and aquifers properties. In addition, [23], introduced Real Time Thermal (RTTR) into DTS system in an attempt to overcome the uncertainties associated with DTS applications in hydrologic science. DTS had also been compared with high-sensitivity sensor for estimation of stream temperature. The results of the research revealed that DTS has an edge as it provides a higher spatial and temporal resolution [14]

2.2.5 Oceanography and Geothermal

The DTS technology had also been employed in other areas of study like oceanography and geothermal engineering. [26], in their research, they discussed the potential of DTS in oceanographic applications. They deployed the technology to detect air/sea boundary. However, the success of the research was significantly hampered by ocean dynamic, inherent noise, and suboptimal calibration in such adverse environment.[13], In an attempt to further enhance the potential of DTS, they designed, implemented, and tested a distributed ultra-high temperature sensing system. The sapphire optical fiber designed by them was able to operate under a temperature as high as 1400^0C. Although their research could be considered a success, commercialization of such sensor economically remains a concern. In sewage treatment, [20], applied DTS to monitor temperature variation in a waste-water system. The objective was to determine the factors that contribute to temperature variation in the system and the degree of mixing of the waste-water system.

Finally, In the steel industry, DTS has been employed to measure temperature profiles during steel casting process. The DTS was also used to monitor aluminium solidification. These applications reinforce the ability of the DTS to survive extremely high temperature [17].

3.0 Challenges and Future Research Opportunities

It is an open secret that despite the resounding success recorded so far, many fields are still experiencing serious challenges with the application of DTS technology. In atmospheric science, errors introduced through calibration and temperature stratification remain the major obstacle to unleashing the full potential of the DTS technology in the field. Therefore, developing a proper technique to overcome the issues associated with calibration and temperature stratification offers an opportunity for further research in the field. Furthermore, the reliability of the DTS technology in hydrological science has been hampered by calibration, relative humidity, and noise introduced by surface and groundwater velocities. Therefore, developing a reliable calibration technique and a method of minimizing the effects of surface and groundwater flow will undoubtedly enhance the potential of DTS technology in hydrological science. Moreover, in oceanography, the potential of DTS technology is currently being limited by Ice penetration and inability to achieve long term operation for non-recoverable sensors, ocean dynamic, inherent noise, and suboptimal calibration in such adverse environment. Therefore, developing methods of overcoming these challenges through cutting-edge research will significantly enhance the potential of the DTS technology in the field of Oceanography.

4.0 Conclusion

A comprehensive review of the theory and applications of the Distributed Fiber Optics Temperature Sensing (DTS) technology in Engineering, Oceanography, Atmospheric Science, Hydrology, and Geological Science has been carried out. In this study, we investigated the potentials of Distributed Temperature Sensing (DTS) in Oceanography and Atmospheric Science, fields often neglected by authors who had previously written articles on the subject of Distributed Temperature Sensing (DTS). Furthermore, some challenges associated with the application of the Distributed Temperature Sensing (DTS) technology in Hydrology, Oceanography, and Atmospheric Science were identified and discussed. Additionally, we have also outlined some opportunities for future research on the applications of Distributed Temperature Sensing (DTS) in Oil & Gas, Hydrology, Geological Science, Oceanography, and Atmospheric Science. This study shows that the potential of Distributed Temperature Sensing (DTS) is currently being hampered by calibration issues, noise introduced by instruments and environmental conditions, site accessibility, as well as equipment deficiencies. Furthermore, the study also shows that Oil & Gas industry has embraced the technology the most, as it has been applied to detect leakages in pipes, estimate flow velocity in pipes and reservoirs, and also develop profiles for injection and production processes. Conversely, Oceanography has embraced the technology the least as its deployment is currently being hampered by some of the challenges discussed above. In conclusion, the Distributed Temperature Sensing (DTS) technology has great potential in Hydrology, Atmospheric Science, as well as Oceanography if the challenges outlined in this study are properly addressed through cutting-edge research. This therefore offers opportunities for future research on the subject of Distributed Temperature Sensing (DTS).

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1. Declarations

Author Contributions

The following statements should be used:

Conceptualization, **T.S.A., D.A** and **A.M**.; methodology, **T.S.A., D.A** and **A.M** ; investigation, **T.S.A** and **D.A**.; resources **T.S.A** and **D.A** ; writing—original draft preparation, **T.S.A**.; writing—review and editing, **T.S.A** and **A.M**.; All authors have read and agreed to the published version of the manuscript.

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