Depth of Burial State Monitoring of a 500 kV HVDC Offshore Power Cable Interconnector using Distributed Fiber-Optic Temperature Sensing

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ABSTRACT

In this work, we present a fast and accurate approach to determine exposed submarine power cable locations based on the measured load and distributed temperature traces. This method, referred to as Depth-of-Burial-Status (DoBS), involves the calculation of the local load-temperature change correlation function. This concept is applied on the 500 kV Skagerrak4 interconnector to determine the exposure locations, and the results are validated by a Remotely Operated Vehicle survey. Based on the DoBS approach, we detected all fully exposed cable sections, in addition to locations with shallow exposures and ducted cable sections in a surveyed offshore length of 22 km.

KEYWORDS

Offshore Cable Monitoring, Exposed Power Cable, Cable Survey, Distributed Temperature Sensing, Depth of Burial Status.

INTRODUCTION

In the last decade, the demand for renewable energies has grown substantially owing to the global commitment to reduce the impact of carbon dioxide emissions from fossil fuels on the environment. Furthermore, the European energy strategy is currently accelerating the transition towards more sustainable energies such as solar and wind to achieve more energy autarky, driven by the actual political impacts. According to the European Commission, offshore renewable energy has the greatest potential to scale up. Based on an actual installed offshore wind capacity of 16 GW [1], the Commission estimates to achieve an installed capacity of at least 60 GW by 2030 with a view to reach 300 GW by 2050 [2]. The increased power capacity implies the installation of more wind farms and submarine power cables, which represent the backbone for offshore energy transmission. Indeed, these cables are commonly buried during the installation process. They may, however, suffer from exposure due to waves, seabed currents, and tidal activities, particularly in the inshore areas.

To reduce the risk of cable damage, and hence eventual long power outage, monitoring of the submarine cables becomes more and more important. In fact, Third-Party Intrusion (TPI) activities such as fishing, trawling, anchoring, or sabotage are known to be real threats, especially when the cables are exposed. According to [3], in the period between 2006 and 2015, 89% of submarine power cable faults with external cause were reported on unprotected cables, where most failures were mainly due to anchor damage. The average mean outage time of the reported submarine cable failures in [3] was estimated to 105 days.

Owing to the optical fibers which are integrated within most state-of-the-art submarine three-core power cables or delivered externally and bundled to single-core cables, continuous monitoring of these assets can be implemented conveniently using distributed sensing techniques, such as Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS). The capabilities of these fiber-optics-based systems include hotspots identification [4], TPI events detection [5], cable-fault localization [6], Real-Time Thermal Rating (RTTR) [7], Depth-of-Burial (DoB) calculation [8], among others.

Conventional DoB approaches are known to provide approximate burial depths of subsea power cables based on the thermal response of the cable to load variations by using DTS measurements, load data histories, and thermal models of the power cable and its surroundings [8], [9]. Thus, such techniques require the precise knowledge of the ambient conditions and thermal parameters of the seabed, depend on the absolute measured temperature, and have limitations on the detectable burial depth.

In practice, the most important feature is often not the burial depth itself, but the state of the cable and its change. By calculating the local load-temperature change correlation function, it is possible to determine the burial state of the cable accurately and fast. The main effect behind our new DoBS approach can be understood as follows: The closer the cable to the water, the faster the dissipated heat can be transported away, and hence the lower the temperature change measured by the fiber upon a load change. Such exposure features can be identified by analyzing solely the power cable load and the temperature traces collected by a DTS instrument. Hence, the DoBS method does not require any precise knowledge of the ambient conditions and thermal parameters of the seabed and does not depend on the absolute temperature values measured along the cable. This significantly reduces the commissioning effort, avoids any uncertainties caused by measurement deviations, and is especially applicable to retrofits, where soil sample data might be outdated or not available at all.

THEORY

Various approaches to calculate the burial depth from DTS temperatures exist in literature [8], [9], [10]. They all tackle the problem by solving the corresponding diffusion equation in the vicinity of the cable, with or without convective terms. However, there are several issues with this approach: the absolute temperature of the environment must be known (or has to be estimated from the measurements), ambient parameters (like the thermal resistivity of the sea ground) might not be known precisely, material and loss parameters of the cable itself might also be unknown or inaccurate. The calculation of the heat losses required for the solution of the diffusion equation is usually performed according to the IEC 60287 specifications [11]. However, due to the dynamic operation, this calculation can be considered here as conservative. Therefore, biases towards overestimating the losses are introduced. Furthermore, often only a one-dimensional approximation to the two-dimensional diffusion equation is solved, which introduces further inaccuracies to the result.

In a subsea power cable, there are three main drivers of temperature variations along the cable route: external temperature variations (e.g. water temperature), variations in the sea ground conditions, and burial depth variations. In a hypothetical stationary state with constant heat loss, it is not possible to distinguish between these effects in a pointwise calculation. However, while a change in the burial depth does affect the relative temperature response to load variations, a change in the external temperature does not. If cable sections of constant sea ground conditions are identified, the burial depth is the main driver of spatial variations in the temperature response. Our findings show that this effect can be captured and quantified as a correlation function between measured quantities without employing any thermal modelling.

The central quantity in our analysis is the load-temperature change correlation function defined at location i as

$$C_i(\Delta t) = \sum_t^{T_{av}} I(t) \cdot \left(T_i(t+\Delta t) - T_i(t)\right), \qquad [1]$$

where $I(t)$ is the cable load at time t, and $T_i(t)$ denotes the measured DTS temperature at time t and location i. The calculation of $C_i(\Delta t)$ only depends on local temperature differences. Thus, the absolute temperature drops out, and the result is independent of the external temperature level (this is only true to first order as there are non-linear effects from convection, and the thermal resistances of the conductors have a temperature dependence).

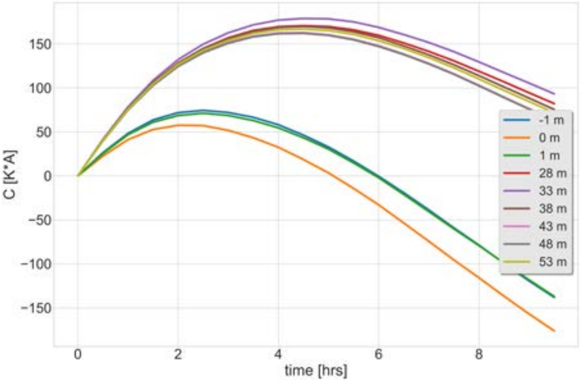

Fig. 1: Load-temperature change correlation function at some locations along a subsea power cable in the North Sea. The behavior at three locations (-1 m, 0 m, 1 m) is apparently different. At those locations the cable is unburied, while at the other locations it is buried in the sea ground. This observation can be quantified to detect exposed cable sections in real-time.

The temporal behavior of $C_i(\Delta t)$ at different locations is shown in Fig. 1. The interpretation is as follows: at $\Delta t = 0$, a short pulse of heat is emitted in the conductor core, and the curves show how the fiber temperature changes in response to that fictional energy pulse. As there is a finite distance from the conductor cores to the position of the fiber, it takes some time for the heat to diffuse, and the fiber temperature reaches its maximum value only after 3-5 hours. When the maximum has been reached, the correlations start to drop monotonically. In the figure, we show three locations where the correlation function behaves quantitively differently (colored blue, orange, and green, respectively). Here, the maximum correlation is much lower compared to the other locations. In addition, at those locations, the maximum correlation is reached earlier, and the subsequent temperature drop is much faster and steeper. At these three locations, the cable is exposed and surrounded by water. At the other six locations, the cable is buried at about two meters. Data is taken from a three-core cable in the North Sea. The example data for the cable exposure are taken from the onshore-offshore transition, where the cable leaves the Horizontal Directional Drilling (HDD) duct. It is known that the cable lies in the water for a few meters at this transition.

The maximum values of the correlation function turn out to be a very good predictor for the burial depth of the cable. When compared to the values of neighboring locations, a smaller maximum value indicates a lower burial depth. In the figure, the maximum correlations are smaller by approximately a factor of three at the unburied locations. As the value of $\max\left(C_i(\Delta t)\right)$ depends on the load level in the considered period, we normalize the results by its median value along the cable (or in cable sections of non-varying thermal environment). We call the normalized maximum value of the local correlation function the *thermal response*. By construction, a value of 1 indicates typical burial conditions, while a very low value indicates a cable exposure.

Eq. [1] has no free parameters other than the timescale T_{av} on which data is averaged. Reasonable values are in the range of 1-4 weeks. For the results reported below, it was chosen to be 20 days. To detect cable exposures, it is sufficient to set a threshold on the thermal response. From our experience, this is in the range from 0.3 to 0.4. However, it might depend on the installation details, like the fiber position or the cable size.

FIELD RESULTS

In this paragraph, we demonstrate the effectiveness of our method by comparing the calculated DoBS results with the exposed locations determined during a Remotely Operated Vehicle (ROV) survey on the 500 kV high-voltage Skagerrak4 interconnector between Norway and Denmark, conducted in August 2022. Based on our DoBS solution, we were able to correctly determine the exposed cable positions, in addition to locations with shallow exposures and ducted cable sections in a surveyed offshore length of approximately 22 km.

Skagerrak4 is an interconnector between two transmission system operators: Statnett in Norway and Energinet in Denmark. The interconnector facilitates more renewable energy production in both countries and ensures an increased security of power supply. Skagerrak4 has a capacity of 700 MW and comprehends a 137 km offshore cable and a 12 km onshore cable in Norway. The power cable is a Mass-Impregnated Non-Draining (MIND) cable with a typical fluctuating load profile up to 1430 A. The cable was installed in 2013 at a depth of 0.5 m to 2 m below seabed using the CAPJET trenching system. The water depth along the entire offshore cable ranges from 0 to -532 meters relative to the Main Sea Level (mMSL).

Fig. 2 shows the location of Skagerrak4 interconnector overlaid with water depths based on the EMODnet Digital Terrain Model (DTM) [10].

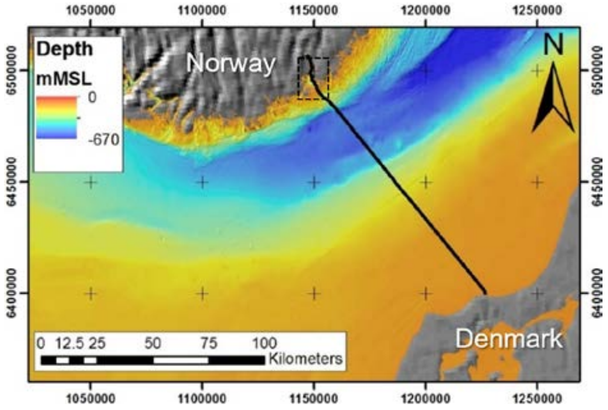

Fig. 2: Location of the Skagerrak4 interconnector between Norway and Denmark overlaid with water depths (courtesy of M. Erdmann [10]). The dashed rectangle represents the surveyed cable section in August 2022.

For this project, an N4525A DTS instrument is used with a maximum reach of 70 km for temperature monitoring, hotspot detection, and DoBS calculation. The sampling interval and spatial resolution are configured to 2 m and 4 m, respectively, while the measurement time is set to 90 min based on an update time of 30 min and a sliding average factor of 3. Additionally, an N5200A DAS system with a range of 80 km, a gauge length of 20 m, and a pulse rate of 0.5 kHz is deployed for cable fault localization. Moreover, the Distributed Temperature Gradient Sensing (DTGS) measurement data provided by the DAS system is combined with the temperature traces measured by the DTS instrument at long distances in order to significantly enhance the temperature resolution. We call this method, the enhanced-DTS (eDTS) technique [12]. Both measurement instruments are installed at the Norwegian side and are connected to a Fiber Optic Cable (FOC), which is bundled to the power cable.

The temperature profiles are collected every 30 min, and an updated DoBS profile is generated every 12 h. Commissioning of the DoBS engine was achieved a few months prior to the survey within one day without any additional information of the power cable parameters and seabed properties, and the first results were obtained within approximately one month after system configuration. This shows a clear advantage in comparison to the time-consuming thermal model generation of other DoB solutions, where configuration can take up to one month, and first calculations may be obtained after several months.

Fig. 3 illustrates a measured temperature profile on 11.08.2022 and the calculated DoBS results of the first 22 km offshore segment, starting from the Norwegian side. It can be seen in the graph that most of this submarine cable section is buried, whereas some locations exhibit eventual exposure probably due to seabed activities, especially at the inshore section. While some cold spots may be an indication of cable exposure, this statement cannot be generalized since several points with lower temperature than the rest of the cable seem to be covered.

The exposed locations were verified during the ROV survey starting from deep towards shallow water. The cable inspection survey started on 11.08.2022 at 06:07 UTC and finished on 11.08.2022 at 22:51 UTC, without accounting for times of the seafaring to/from the test locations and ROV deploying off/on the vessel deck. The survey was conducted from a fiber position of 34,823 m to 12,788 m, and the corresponding cable section is marked with a dashed rectangle in Fig. 2. The water depth along the surveyed section ranges from -8 to -237 mMSL.

The IKM Merlin WR200 ROV was equipped with an Ultra Short Baseline (USBL) positioning system, a depth sensor, a sound velocity sensor, a Doppler log, a side scan sonar system, a multibeam echosounder R2Sonic MBE 2024, and a High Definition (HD) video camera, allowing to identify the submarine power cable trace and the corresponding exposure locations. Based on the ROV data, we were able to compare all calculated exposure locations with the actual burial state of the cable.

Based on the survey, there exist fourteen distinguishable areas of exposed non-ducted cable where eleven have been clearly identified by the DoBS module and marked by the green dots in Fig. 3. The inset shows an example of the multibeam output at the zoomed-in section as proof for cable exposure. The landfall area at the Norwegian coast is considered as one large exposure section with several unburied portions over a length of approximately 300 m. The other three areas exhibit a very shallow exposure or a single point of exposure and are not labelled by the DoBS module as exposed. Since the spatial resolution of the DTS instrument was configured to 4 m, we believe that a finer configuration would help to identify such locations.

In Fig. 3, there exist five locations (marked by grey dots) which are labelled as exposed, but the survey does not indicate an exposure. For all these locations it is confirmed, by inspection of the corresponding ROV videos, that the cable is covered by rock berms or gravel. Therefore, the heat transport is dominated by convection here, and no temperature-based method can distinguish these locations from true exposures. However, these findings might be of interest to the cable operator since the results can serve as a permanent real-time validation of the DoBS system if the locations are known. In case the locations are not known, they might be considered as additional points of interest that deserve further inspection.

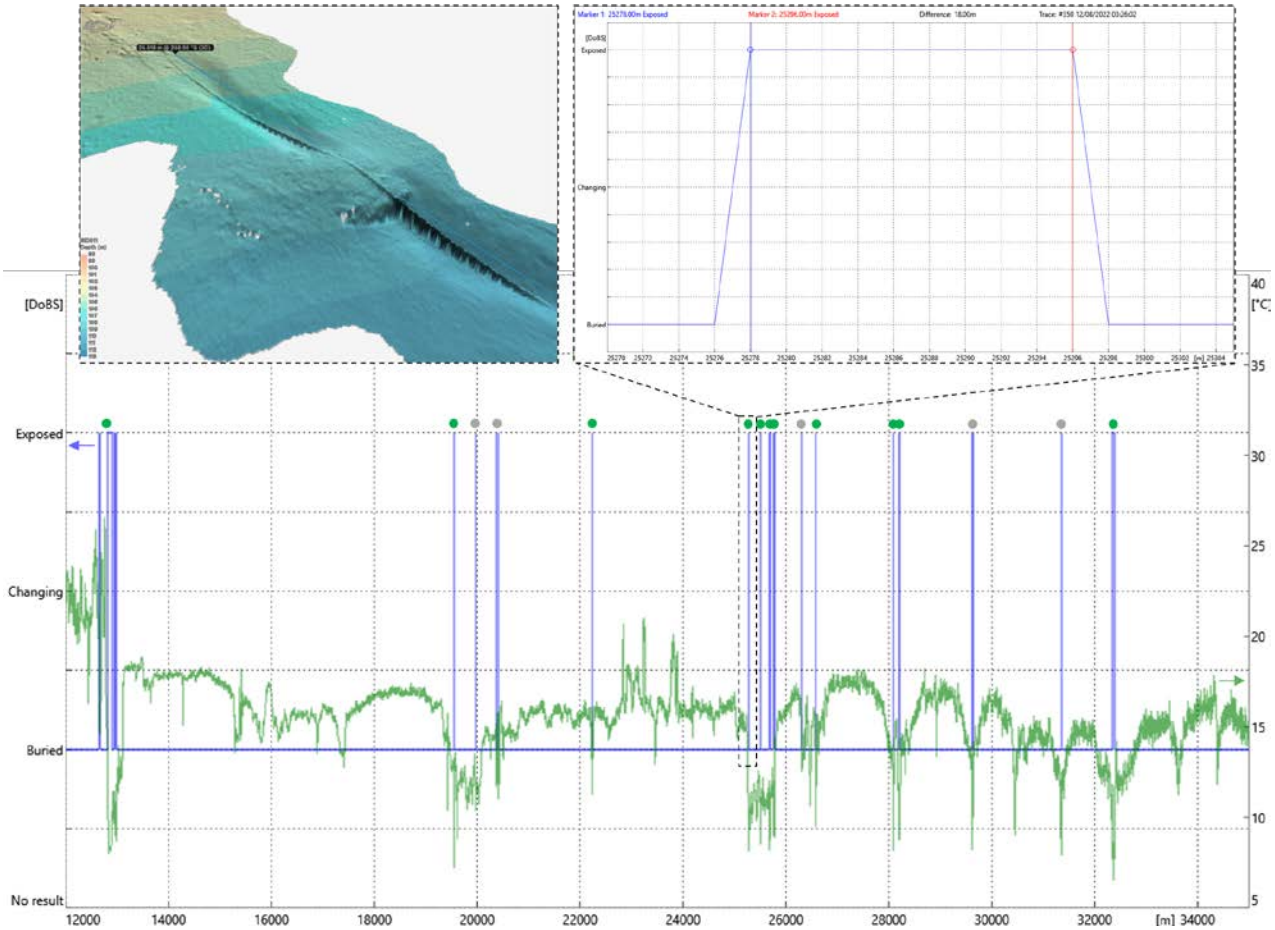

Fig. 3: Measured temperature profile during the ROV survey and calculated DoBS results along the surveyed section of Skagerrak4. The exemplary multibeam graph shows cable exposure proof of the zoomed-in section.

Prior analysis of the survey data, a proper fiber-to-asset mapping was performed to ensure an alignment between the FOC and power cable meter marks. The mapping relied on extracting the acoustic signals produced by the ROV while travelling along the cable and captured by the DAS system. Since the GPS coordinates and cable Kilometer Point (KP) of the ROV location are tracked, an accurate mapping can be achieved. A few tapping tests were also conducted by the ROV arm in the vicinity of the cable for additional verifications. Fig. 4 shows the Frequency Band Energy (FBE) plots in the 8 – 20 Hz range of some acoustic signals produced by the ROV while travelling along the cable at a velocity of 1.7 km/h and during a tapping test.

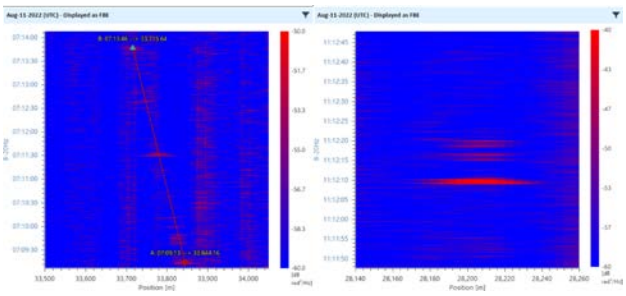

Fig. 4: Vibration signals of the ROV (left) while moving along the cable and (right) during a tapping test in the vicinity of the cable.

In order to analyze the DoBS results in detail, the local load-temperature change correlation function, also denoted here as *thermal response*, is compared with the survey DoB output. For visibility purposes, only an excerpt of the calculated thermal response and the corresponding measured burial depth by the ROV multibeam scanner are shown in Fig. 5.

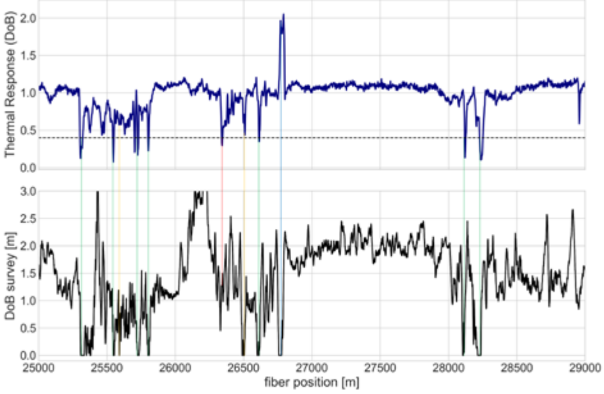

Fig. 5: (Top) calculated thermal response by the DoBS module and (bottom) measured burial depth by the ROV multibeam scanner along a section of the surveyed power cable.

The thermal response is scaled so that a value of 1 reflects typical burial conditions, while low values ≤0.4 indicate a cable exposure. It can be clearly seen that the DoBS calculation and the field results are in good agreement with regard to the exposed sections (green lines in Fig. 5). Also, at the fiber positions 25,569 m and 26,484 m which have not been labelled as exposed by the DoBS engine due to shallow exposure, the thermal response amounts to 0.58 and 0.43, respectively, slightly above the adjusted threshold for cable exposure qualification (orange lines). This means that the DoBS technique is showing a signal and would identify these exposed locations if the threshold is adjusted slightly higher and/or the DTS measurement parameters are refined.

It can also be seen in Fig. 5 that there exists a location with a high thermal response of ~2 (blue line). This location denotes a high thermal confinement, indicating a cable installation in a duct or other kind of Cable Protection Systems (CPS). Even though six of these locations have been identified by the survey as exposed, the installation state cannot be recognized by the multibeam scanner, which shows the strength of the DoBS engine. In sum, eight ducted power cable locations have been identified by the DoBS along the surveyed section.

A detailed comparison between the ROV survey and DoBS results at the actual exposed locations is summarized in Table 1.

Table 1: Exposure locations of the surveyed power cable based on the ROV and the corresponding results of the DoBS module.

Fiber Position [m]	ROV	DoBS	DoBS Correlation
12,788–13,091	exposed	exposed	~0.2
19,418–19,442	exposed	ducted	~1.8
19,568–19,570	exposed	exposed	~0.3
22,256–22,257	3-6 cm coverage	exposed	~0.3
22,843–22,855	exposed	ducted	~1.9
23,260–23,265	exposed	ducted	~2
23,785–23,896	exposed	ducted	~2
24,186–24,201	exposed	ducted	~2
25,285–25,359	exposed	exposed	~0.2
25,525–25,531	exposed	exposed	~0.2
25,569	exposed	buried	~0.6
25,705–25,714	exposed	exposed	~0.2
25,780–25,788	exposed	exposed	~0.3
26,472–26,487	exposed	buried	~0.5
26,583–26,596	exposed	exposed	~0.3
26,742–26,762	exposed	ducted	~1.8
28,094–28,097	exposed	exposed	~0.2
28,204–28,227	exposed	exposed	~0.1
30,442	exposed	buried	~0.6
32,339–32,360	exposed	exposed	~0.2

CONCLUSION

We have implemented a fast and accurate approach to calculate the depth of burial state of submarine power cables based solely on the load data and distributed temperature traces. The effectiveness of this method is demonstrated by comparing the calculated DoBS results with the exposed locations determined during an ROV survey on the high-voltage Skagerrak4 interconnector between Norway and Denmark. All exposed non-ducted cable areas have successfully triggered a DoBS signal with a correlation value from ~0.1 to ~0.6. The DoBS signal has also identified ducted cable areas which exhibit a higher correlation value of ~1.8 to ~2. At the five locations covered by rock berms and gravel, the heat transport is dominated by convection, and no temperature-based method can distinguish these locations from true exposures.

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GLOSSARY

CPS: Cable Protection System
DAS: Distributed Acoustic Sensing

DoB: Depth-of-Burial
DoBS: Depth-of-Burial-Status
DTGS: Distributed Temperature Gradient Sensing
DTM: Digital Terrain Model
DTS: Distributed Temperature Sensing
eDTS: Enhanced Distributed Temperature Sensing
FOC: Fiber Optic Cable
HD: High Definition
HDD: Horizontal Directional Drilling
KP: Kilometer Point
MIND: Mass-Impregnated Non-Draining
mMSL: meters Mean Sea Level
ROV: Remotely Operated Vehicle
RTTR: Real-Time Thermal Rating
TPI: Third-Party Intrusion
USBL: Ultra Short Baseline