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LEADING PIPELINE RESEARCH

Real-Time Detection of Mechanical Impact on Pipelines via Cathodic Protection

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Of

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Abstract

Third-party damage is a leading cause of pipeline failures worldwide, accounting for up to 50% of incidents. Although it is important for operators to be informed in real time of mechanical shocks on their pipelines, there is no satisfactory technology to meet this need at this time. The complex implementation and cost of existing solutions hinder their large-scale deployment.

The SPADE company has developed and patented a technology for real-time detection of mechanical shocks on steel pipelines, based on the cathodic protection current. This technology detects, in real time, aggression, interference, or other disturbance taking place on a pipeline, such as third-party damage, illicit tapping, or contact between the pipe and its casing. SPADE system can be easily integrated into existing installations without any modification.

Under PRCI project number PR-749-223901, the performance of the SPADE technology was validated under real field conditions.

PRCI project team members

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List of Acronyms

FBE	Fusion Bonding Epoxy
PHMSA	Pipeline and Hazardous Materials Safety Administration
CP	Cathodic Protection
PG&E	Pacific Gas and Electric
DC	Direct Current
AC	Alternative Current

1 – Executive Summary

The SPADE company has developed and patented a technology based on monitoring the cathodic protection current, for real-time detection of mechanical impacts on steel pipelines, of illegal tapping, and of a short electrical circuit between pipe and casing. In this project, the SPADE technology was validated by carrying out field tests with pipelines under typical operating conditions. The value of the SPADE technology was shown for detecting mechanical impact on pipelines with FBE and coal tar enamel coatings, for detecting an electrical short circuit between pipe and casing, and for detecting illegal tapping – all in real time, so that the pipeline operator can be informed – in real time – of damage to the pipeline and can respond proactively.

2 – Introduction

Worldwide, approximately 50% of pipeline failures are caused by third party damage, typically by impact of an excavator. Since 2017, the SPADE company has developed their technology for pipeline operators to detect damage on pipelines in real time based on signals from the cathodic protection system caused by mechanical impact, illegal tapping, and electrical shorting between pipe and casing. Real-time detection of these unexpected occurrences on a pipeline makes timely response and corrective action by the pipeline operator possible, to ensure continued pipeline reliability, and enhanced public safety, environmental protection, and energy deliverability.

Under PRCI Agreement Number PR-749-223901, SPADE has carried out pilot field tests to validate the SPADE technology for real-time detection of mechanical damage on pipelines with FBE and coal tar coatings, an electrical short circuit between a pipe and its casing, and illegal tapping. Field tests were carried out in soils of resistivity less than 500 ohm-cm and also in soils of resistivity 876 ohm-cm.

3 – Value to Members

The value of the SPADE technology arises from the value of detecting – in real time – unexpected intrusions that damage operating pipelines and can lead to pipeline failure. In addition, it will mitigate the financial and environmental costs related to accidents and gas releases.

SPADE enables operators to monitor CP current at rectifiers in order to detect and/or evaluate, in real time, third-party damage and/or illegal tapping. This PRCI project allows pipeline operators to identify the operational conditions for successful application of this technology. As a consequence, for example, operators will be able to decide when and where they can use such a technical solution with efficiency and confidence. When applicable, operators will be able to improve detection of third-party impact at minimal cost, improving pipeline safety and operational efficiency.

At this stage, the accuracy of the impact localization corresponds to the distance between two rectifiers. SPADE's data processing efforts aim to improve the accuracy to the spacing between two cathodic protection test stations.

4- Background

Pipeline operators are confronted with a major challenge: Monitoring and detecting mechanical impacts on their network. Currently applied methods allow detection of such events albeit with delays that can reach several years, risking provoking major incidents, including rupture. According to the PHMSA data in Figure 1, excavation damage is the most common cause of pipeline incidents.

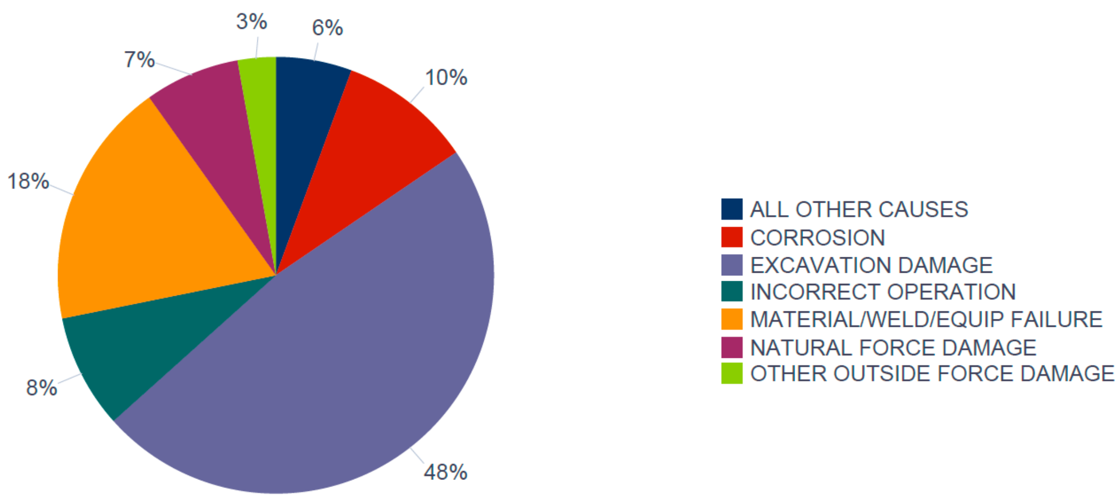


Figure 1. Causes of pipeline incidents. Source: PHMSA Pipeline Incident 20 Year Trends https://www.phmsa.dot.gov/data-and-statistics/pipeline/pipeline-incident-20-year-trends.

Table 1. Significant Incidents due to Mechanical Damage over 20-year period: 2003 – 2022

Cause of Incident	Number of Incidents	Fatalities	Injuries	Cost, Cur-rent- Year $	Average Cost, $
Operator/Contractor Excavation Damage	130	4	32	111,629,853	858,691
Previous Damage due to Excavation	42	2	10	61,024,284	1,452,959
Third Party Excavation Damage	744	64	231	592,239,444	796,021
Total Excavation Damage	916	70	273	764,893,581	835,037
Intentional Damage	35	8	26	23,307,488	665,928
Previous Mechanical Damage	22	0	1	41,282,824	1,876,492
TOTAL	973	78	300	829,483,893	852,501

Data from PHMSA website, accessed on September 8, 2023: https://portal.phmsa.dot.gov/analytics/saw.dll?Go

In Table 1, the causes and costs of pipeline incidents over a 20-year period, 2003 – 2022, related to excavation damage and mechanical damage are reported. As listed in Table 1, an estimate of the average cost of one incident of external damage is about $850,000.

In Tables 2 and 3, the gas release per year from external damage and the activity equivalent, respectively, are presented.

Table 2. Gas Releases from External Damage, Gas Pipelines, 2010-2023 from PHMSA Data

Year	No. of Incidents	Volume Gas Released, Thousand standard cubic feet	Fatalities	Injuries	Cost, $	Cost in 2023 dollars
2010-2023	250	2,323,777	13	33	102,615,377	118,753,114
Average per year		169,991	0.95	2.4	7,506,611	8,687,133

Table 3. Gas Release and Activity Equivalent

	Volume Natural Gas Released, Thousand standard cubic feet	Activity Equivalent*
Average Release per Year	169,991	21,615 barrels of oil consumed

*Calculated using U.S. EPA Gas Equivalencies Calculator, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results

SPADE has developed and patented a technology based on monitoring the cathodic protection current, initially for real-time detection of mechanical impacts on steel pipelines. SPADE is able to discriminate impacts by type of aggression, such as mechanical impact, pipeline/casing electrical short, illegal tapping, lightning strike, etc. Steel pipelines are instrumented with a data acquisition module for continuously monitoring the electric currents applied by the CP system. Changes in current output are analyzed directly at the cathodic protection rectifier where SPADE is installed.

SPADE's technology was developed by conducting research and field studies over 17 years:

- 2005-2006: Study on stray currents (AC/DC), patent covering an electronic drainage system.
- 2010: Theorizing stray currents (Wheatstone bridge)
- 2011- present: Drainage system deployed on networks of major European operators
- 2018-2020: Development of SPADE's hardware and algorithms. Intensive field trials on GRTgaz' network in France.
- Nov. 2021: Successful official pilot at GRTgaz network, shown schematically in Figure 2. The hardware that is used in the SPADE demonstrator is illustrated in Figures 3A and 3B.

- Nov. 2022: SPADE was awarded a PRCI contract, ROW-1-01 to validate the technology through pilot projects under real field conditions. PG&E and GRTgaz are the co-leads along with 7 participants: Colonial Pipeline, DCP Midstream, Kinder Morgan, Marathon, Shell, TotalEnergies and TransGas.
- June 29, 2023: Pilot project successfully completed on PG&E's pipeline at Hollister. Across 90% of the pipeline section, the coating is coal tar applied in 1950, the remaining 10% is FBE-coated. The outcome was conclusive; an excavator's impact was detected in real time from a distance of over 6 miles.
- September 13, 2023: Pilot project on a GRTgaz pipeline at Brive-la-Gaillarde, France. Despite the presence of stray currents (DC/AC), the pilot results were positive. The excavator's impact as well as the illegal tapping on the pipeline were detected in real-time from 9.2 miles.
- October 4, 2023: Pilot project on a GRTgaz pipeline at Fontainebleau, France. Real-time detection of mechanical impact in a soil resistivity of 876 ohm.m.

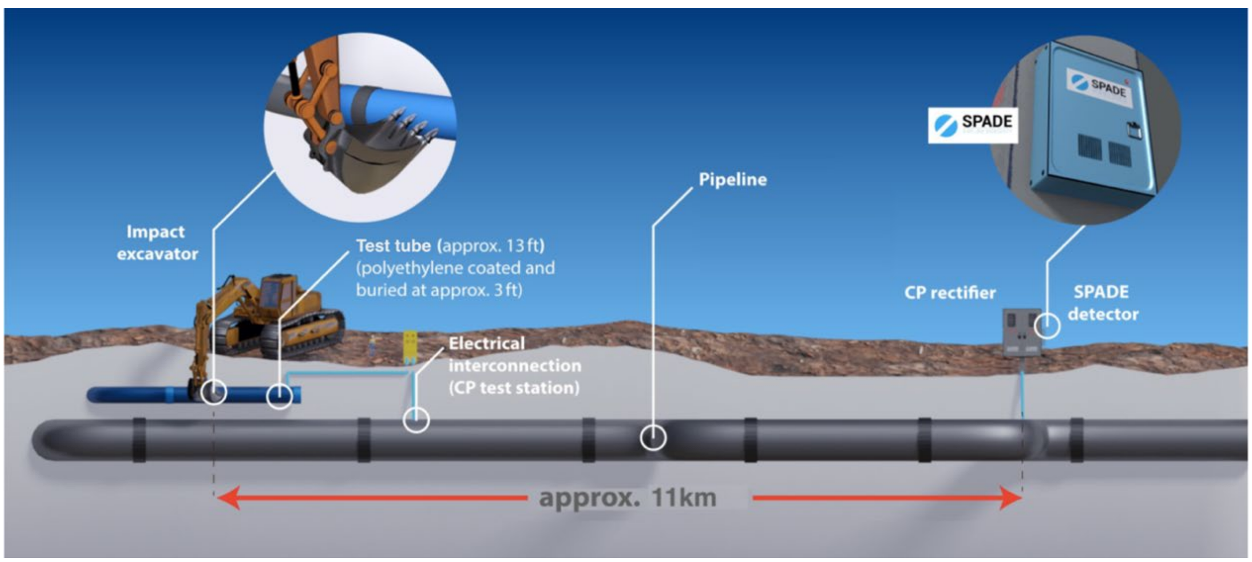


FIGURE 2. Schematic of the SPADE pilot at GRTgaz

5 – Approach

5.1 – SPADE System

The SPADE system has been designed to monitor the characteristics of the cathodic protection system during pipeline operation and to identify, in real time, changes caused by mechanical damage, illegal tapping, and a short circuit between pipe and casing.

For developing a commercial SPADE system for field use during pipeline operation, a SPADE demonstrator has been designed and constructed. The main components of the SPADE demonstrator are:

1. A custom printed circuit board (PCB) to collect inputs, provide alarm indication interfaces, and collect and condition the signal from the cathodic protection rectifier station. The PCB provides circuit protection, scaling, amplification, and selectable filters for four cathodic protection signal channels:
    a. Cathodic protection voltage
    b. Cathodic protection current
    c. Wheatstone bridge circuit
    d. General-purpose channel for reference electrode

2. National Instruments Compact Realtime I/O system (cRIO) for data acquisition and to provide a computing system for user interfaces, data storage, communications, and signal processing to implement the SPADE detection algorithm.

3. Power system with global (85V – 265V, 50/60 Hz) AC-DC power supplies to create the operating DC voltages for the electronics. Fuses and circuit breakers protect the system from electrical faults.

Compared with the demonstrator, the industrial version of the SPADE system, released in December 2023, is smaller, less expensive, and can be operated over an expanded range of environmental conditions. Noteworthy differences compared with the demonstrator are:

1. An industrial-rated computing module for digital input status monitoring, digital control, and to provide the user interfaces, data storage, communications, and signal processing required.

2. Interfaces to deploy and develop satellite modem capacity

3. The power system provides secondary over-current and over-voltage protection to supplement the primary AC mains protection of the cathodic protection station.

5.2 – Field Trials - Procedures

In the Scope of Work, there are eight tasks that require field work to be carried out. The tasks with this requirement are listed in Table 1 along with the locations of the field work at PG&E in California and GRTgaz in France.

Table 4. Eight Tasks for Field Trials

Task Number	Task	Location of Field Work
1	Real-time detection of electrical short between pipe and casing	Brive-la-Gaillarde, France
2	Real-time detection of mechanical impact on FBE-coated pipeline	Hollister, California
3	Real-time detection of mechanical impact on coal tar-coated pipeline	Hollister, California Brive-la-Gaillarde, France
4	Real-time detection at 6 miles distant from point of mechanical impact	Hollister, California Brive-la-Gaillarde, France
5	Real-time detection of mechanical impact on pipeline with AC/DC interference	Brive-la-Gaillarde, France
6	Real-time detection of mechanical impact on pipeline in soil resistivity < 500 ohm.m	Hollister, California Brive-la-Gaillarde, France
7	Real-Time detection of mechanical impact on pipeline in soil resistivity > 500 ohm.m	Fontainebleau, France
8	Real-time detection of illegal tapping	Brive-la-Gaillarde, France

5.2.1 Task 1 – Real-Time Detection of Electrical Short between Pipe and Casing

For Task 1, the field trial was conducted on March 17, 2023, on the GRTgaz pipeline network at Brive-la-Gaillarde, located in the southwest of France, 250 miles south of Paris and 125 miles east of Bordeaux. Over the test pipe length of 15 miles, there were two different pipe diameters, 6 inches and 8 inches, shown on the map, Figure 3 in blue and orange, respectively. The entire length of pipe used in this field trial was coated with coal tar. The 6-inch pipe had been coated in 1960, and the 8-inch pipe in 1967. The casing was located at T01 on the map.

When installing the SPADE System in the field, the following steps must be completed, and the first three listed below must be completed before installation:

1. The existing onsite equipment, such as rectifiers, CP test stations, and high-voltage lines, must be identified and any specific characteristics, such as current drainage and GPS points, noted.

2. To optimize the algorithms for a specific site, electrical recordings on the rectifiers over 72 hours should be established.

3. The electrical recordings on the CP test stations should be synchronized with the recordings on the rectifiers for at least 15 minutes, depending on the local electrical interference and DC and AC stray currents. During this time, faults are simulated to verify their transmission on the line and their recording by the Graphtec data logger installed in the CP rectifier cabinet.

4. Installation of the SPADE equipment and final adjustment of the algorithms.

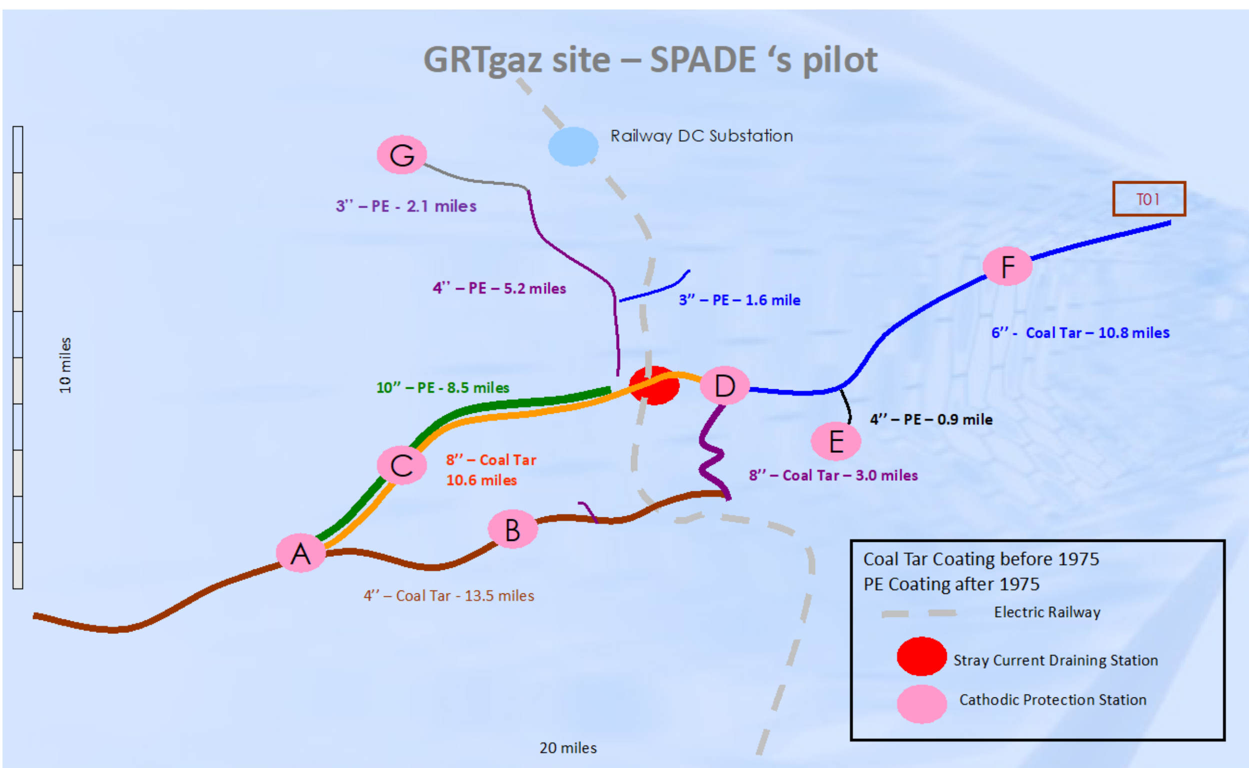


FIGURE 3. Map of GRTgaz network at Brive-La-Gaillarde where the pilot was performed

The SPADE system was installed at the rectifier located at Point C on the map, located approximately 15 miles from the casing at T01.

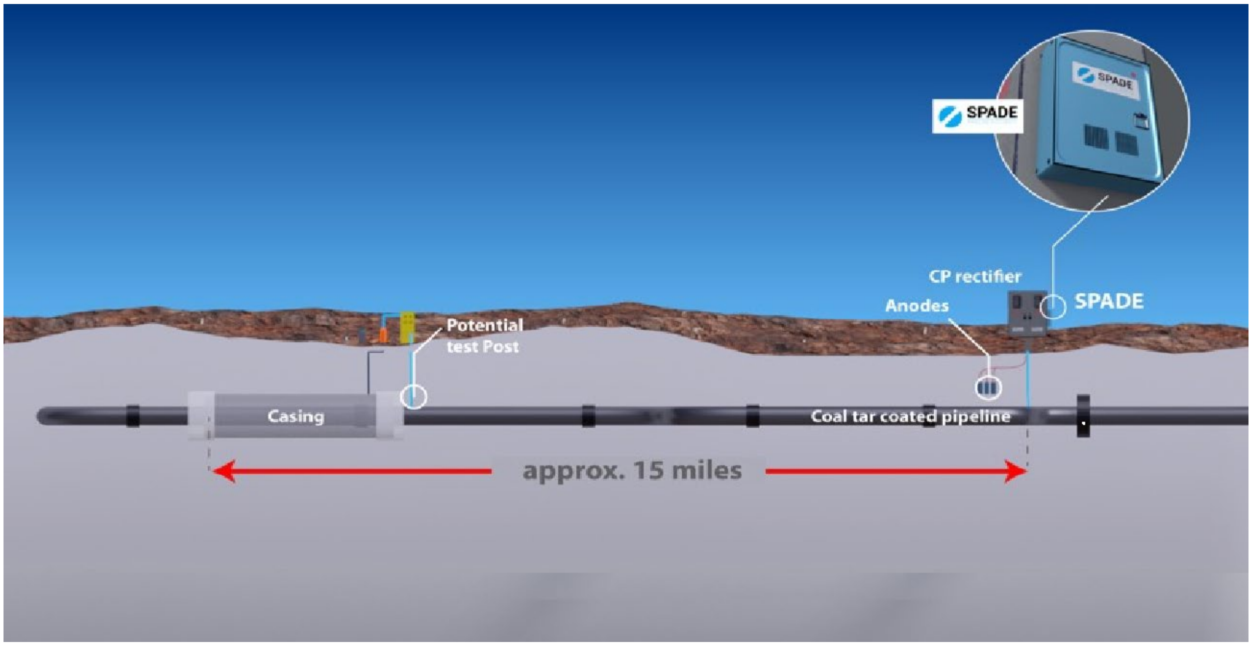


FIGURE 4. Schematic of the pipe/casing electrical pilot

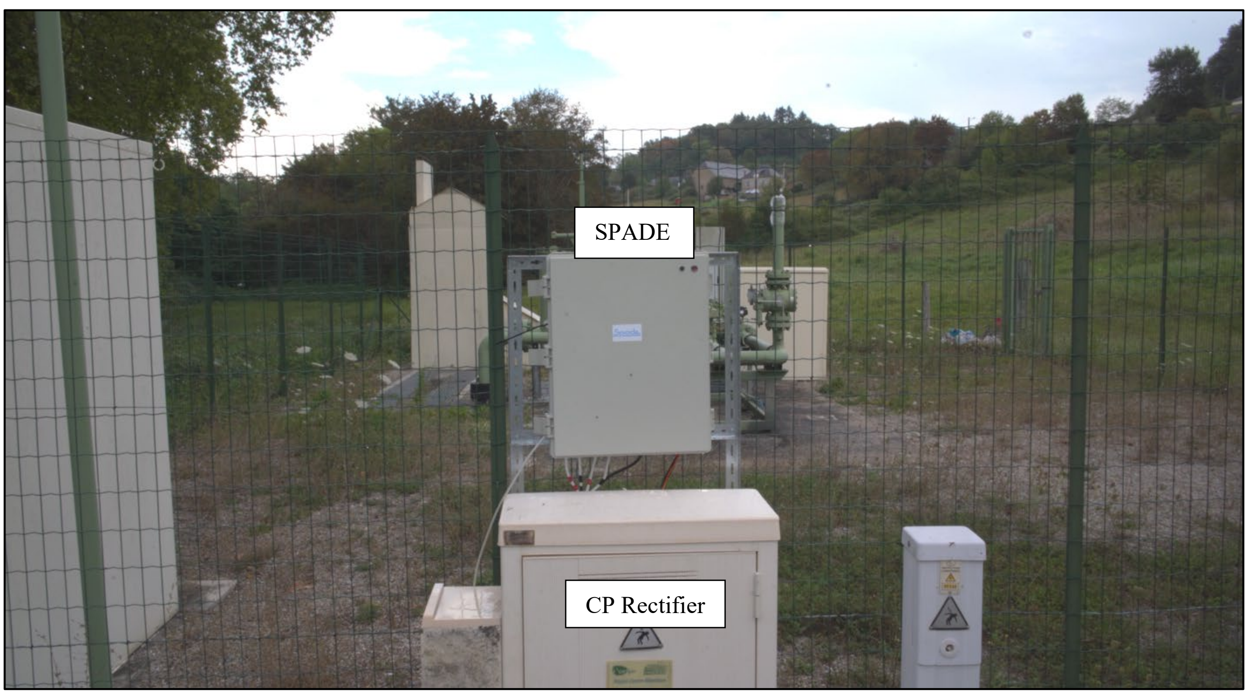


FIGURE 5. Installation of SPADE at the rectifier

An automatic timer was installed at the casing, connecting the pipe to earthing spikes to simulate electric pulses, i.e., contacts between the pipe and its casing. (Figure 6)

FIGURE 6. Earthing spike connected to the automatic timer

The casing, at T01, was connected to the Electric Test Station (ETS) of the pipeline. Signals detected in real time using the SPADE system were recorded using a data logger both before and after the electrical short (Figure 6).

5.2.2 Tasks 2, 3, 4, and 6 – Real-Time Detection of Mechanical Impact on Pipeline – FBE Coated, Coal-Tar-Coated, 6 Miles Distant, Soil Resistivity < 500 ohm.m

The field trials were conducted over four days at a site on the PG&E pipeline network in Hollister, California. The pipeline is 32 inches in diameter, and the length of the pipeline section is 9.6 miles, between rectifiers at 451.4 and 461 miles (Figure 9). The pipeline is buried at a depth of approximately 5 feet in sandy to silty clay soils. The pipeline coating over 90% of the section is coal tar, applied in 1950, and the remainder is FBE.

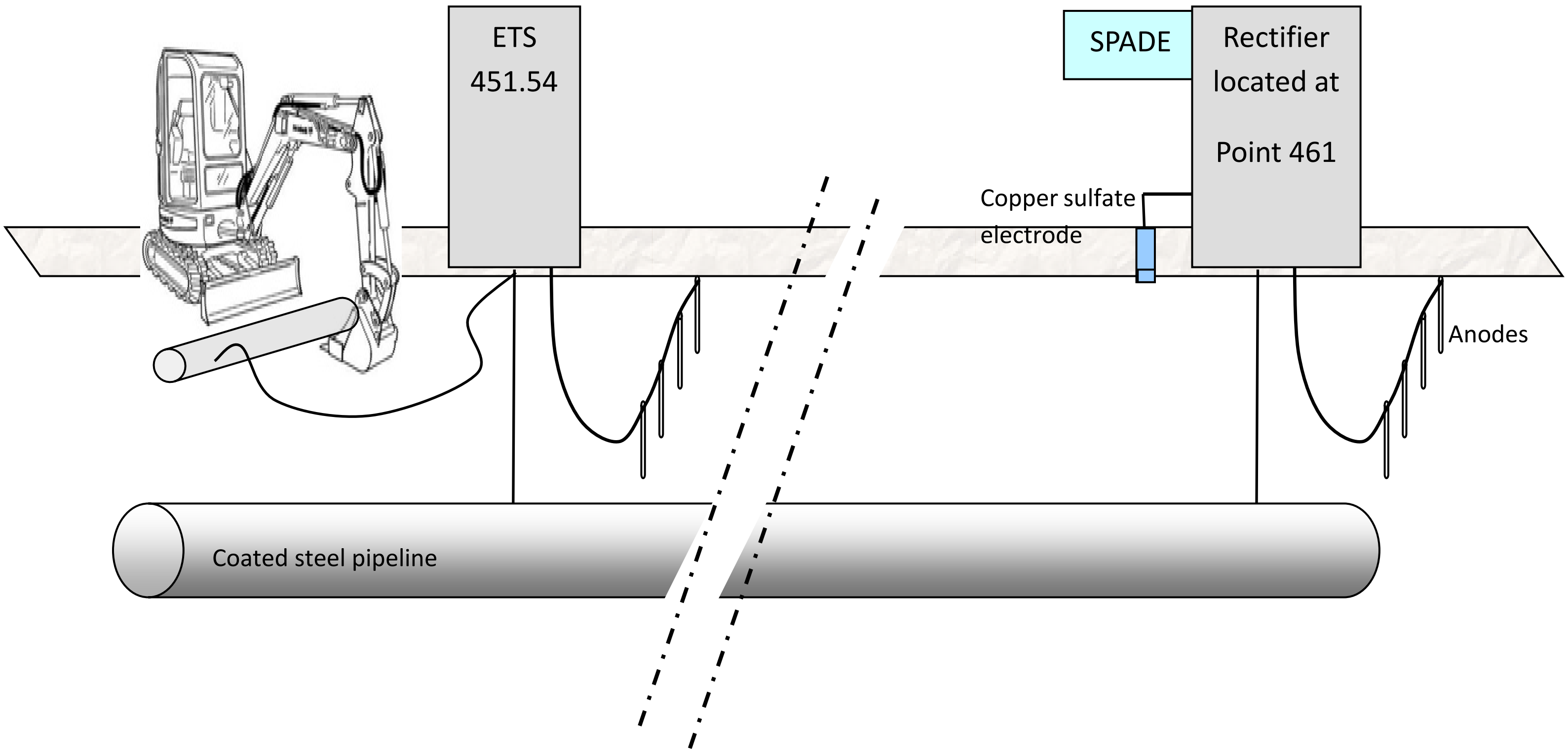


FIGURE 7. Hollister installation drawing

The SPADE System was installed at the rectifier at Point 461 miles.

The test pipe was 6 inches in diameter, 12 feet long, and coated with FBE. Because of safety considerations at PG&E, the test pipe was laid on the ground and was not buried. Using an electrical cable that was soldered on-site, the test pipe was connected to the closest CP test station, at Point 451.54 miles (Figures 8 and 9).

FIGURE 8. FBE-coated test pipe connected to ETS 451.54

An excavator was stationed adjacent to the test pipe. When the excavator impacted the test pipe, signals were recorded at five CP test stations, at 451.54 452.40, 452.98, 455.80, and 457.87 miles, using a Graphtec data logger. Based on 451.54 miles as the point of impact, the distances between the point of impact and the points at which signals were recorded are listed in Table 5.

FIGURE 9. Map of inspection zone with ETSs (Electric Test Points)

Table 5. Distances from Point of Impact to CP Test Stations where Signals Were Recorded

CP Test Station, miles	Distance from Point of Impact, miles
451.54	0.00
452.40	0.86
452.98	1.44
455.80	4.26
457.87	6.33

Figure 10 below shows on the left the installation of the SPADE system at the rectifier.
In Q4 2023, the industrial version of the SPADE will be available, its dimensions are 10x6x3 in. and its weight is 5 lbs.

The inside of the SPADE system is shown on the right of Figure 10. It comprises the acquisition and data processing modules.

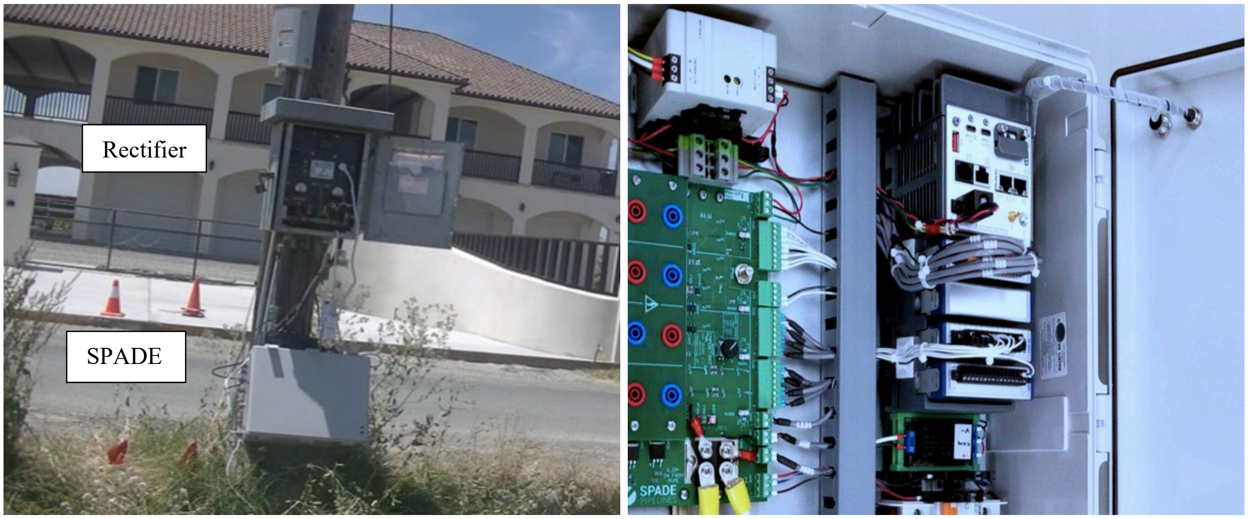


FIGURE 10. SPADE installed at the rectifier SPADE Electronics

As the excavator impacted the test pipe, the corresponding signals were displayed in real-time on the data logger at each of the five ETSs. PG&E representatives could witness the real-time detection of mechanical impact between the excavator and the test pipe.

Figure 10 illustrates the processed signals through SPADE's algorithms at ETS 457.87, i.e., 6.33 miles from the point of impact.

In conclusion, the real-time detection of the excavator's impact from 6.3 miles (10 km) was confirmed on the Hollister pipeline section that is ~90% coal tar-coated (1950) and ~10% FBE-coated.

5.2.3 Task 5 – Real-Time Detection of Impact on Pipeline with AC/DC Interference

For Task 5 (Table 4), the field trial was conducted on the GRTgaz pipeline network at Brive-la-Gaillarde, France. The SPADE system was installed at the rectifier located at Malemort (Figure 9) under electrical power lines, and the test pipe and the excavator were located at Chameyrat. The distance between the 2 locations is 9.2 miles (14.8 km). An electric-powered train frequently travels through this area on the railroad that crosses the site. As a result, stray currents are present, generating DC interference.

The schedule of impact testing included time periods with no impacts, direct impacts by the excavator at a spot on the test pipe and scratching the test pipe by the bucket of the excavator.

5.2.4 Task 8 – Real-Time Detection of Illegal Tapping

As for Tasks 1 and 5, Task 8 was also conducted on the GRTgaz pipeline network at Brive-la-Gaillarde, France, and the same test pipe was used as in Task 5. A company specialized in pipeline tapping was contracted to tap the test pipe. The distance between the test pipe where the tapping was performed and the Malemort rectifier is 9.2 miles (14.8 km).

FIGURE 11. Tapping on the test pipe at Chameyrat

5.2.5 Task7 – Real-Time Detection of Mechanical Impact in Soil Resistivity > 500 ohm.m

The last Task, number 7 (Table 4), was conducted on the GRTgaz network in Fontainebleau, France. The in-service pipeline in this location has a diameter of 8 inches with a coal tar coating applied in 1958.

GTRgaz' on site representatives used a Megger soil resistivity tester. The latter was placed close to the ETS, 4 miles (6.4 km) from the rectifier where SPADE was installed. The Wenner alpha-four pin method was applied for the measurement of the soil resistivity. Four pins were placed at an equal distance, injecting a known current on the outermost electrodes, and recording the voltage between the interior electrodes.

The Wenner formula for measuring the resistivity is the following: $2 * Pi * a * R$.
Where 'a 'is the spacing of the probe and 'R' the resistance measured by the Megger tester.

Accordingly, the soil resistivity at the Fontainebleau site is:
$2 * 3.14 * 1.5$ m $* 93$ ohm.m = 876 ohm.m

FIGURE 12. Resistance measured by the Megger Soil Resistivity Tester

To simulate a mechanical impact on the pipeline, an automatic timer was installed at the ETS, 4 miles from the rectifier that is connected to the SPADE system.

5.3 – Field Trials - Results

5.3.1 Results of Task 1 – Real-Time Detection of Electrical Short between Pipe and Casing

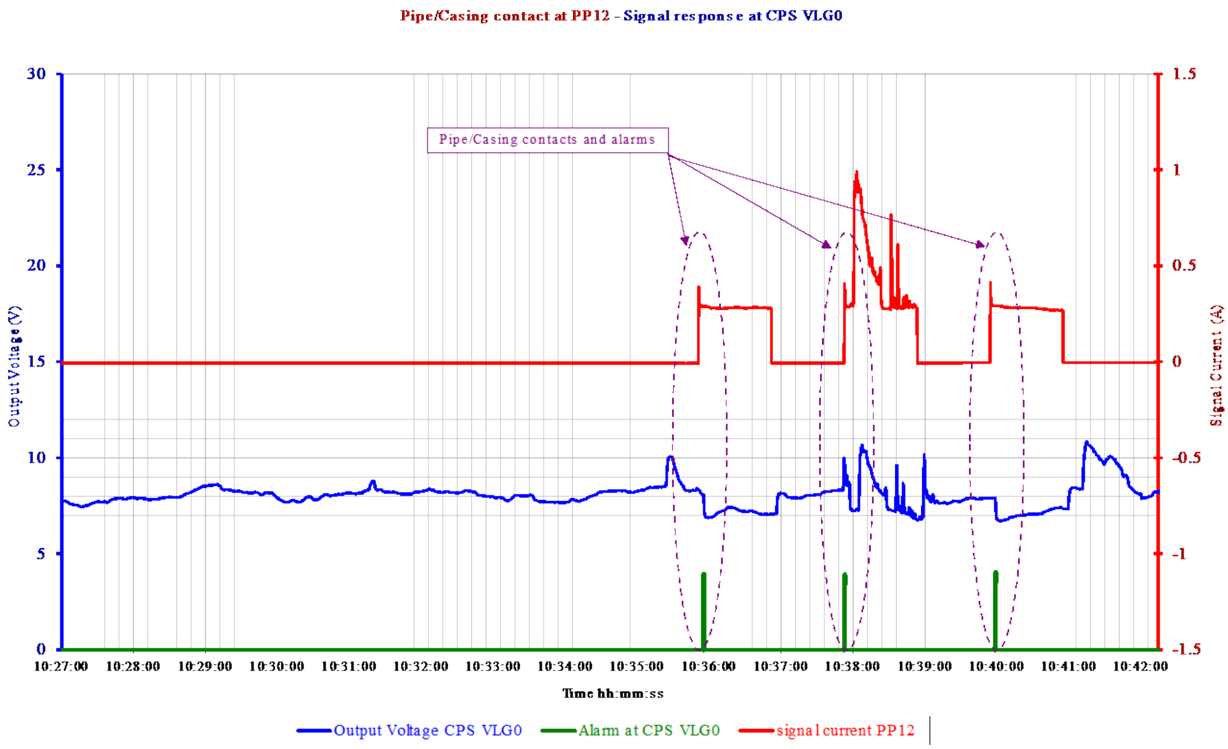


FIGURE 13. Signals of pipe/casing short detection from 15 miles (24 km)

5.3.2 Results of Tasks 2, 3, 4, and 6 – Real-Time Detection of Mechanical Impact on Pipeline – FBE Coated, Coal-Tar-Coated, 6 Miles Distant, Soil Resistivity < 500 ohm.m

Data presented in Figure 14 show real-time detection at 6.3 miles (9.6 km) from the point of mechanical impact on a pipeline with FBE and coal tar coatings in soil of resistivity < 500 ohm.m. The upper graph in Figure 14 shows the raw data from the data logger. The lower graph shows the same data after filtering and processing using the SPADE algorithm. On this lower graph, each × marks an instant in which the excavator impacted the pipeline. There are no false positives (data indicating an impact when there was none), and there are no false negatives (data indicating no impact when there was impact).

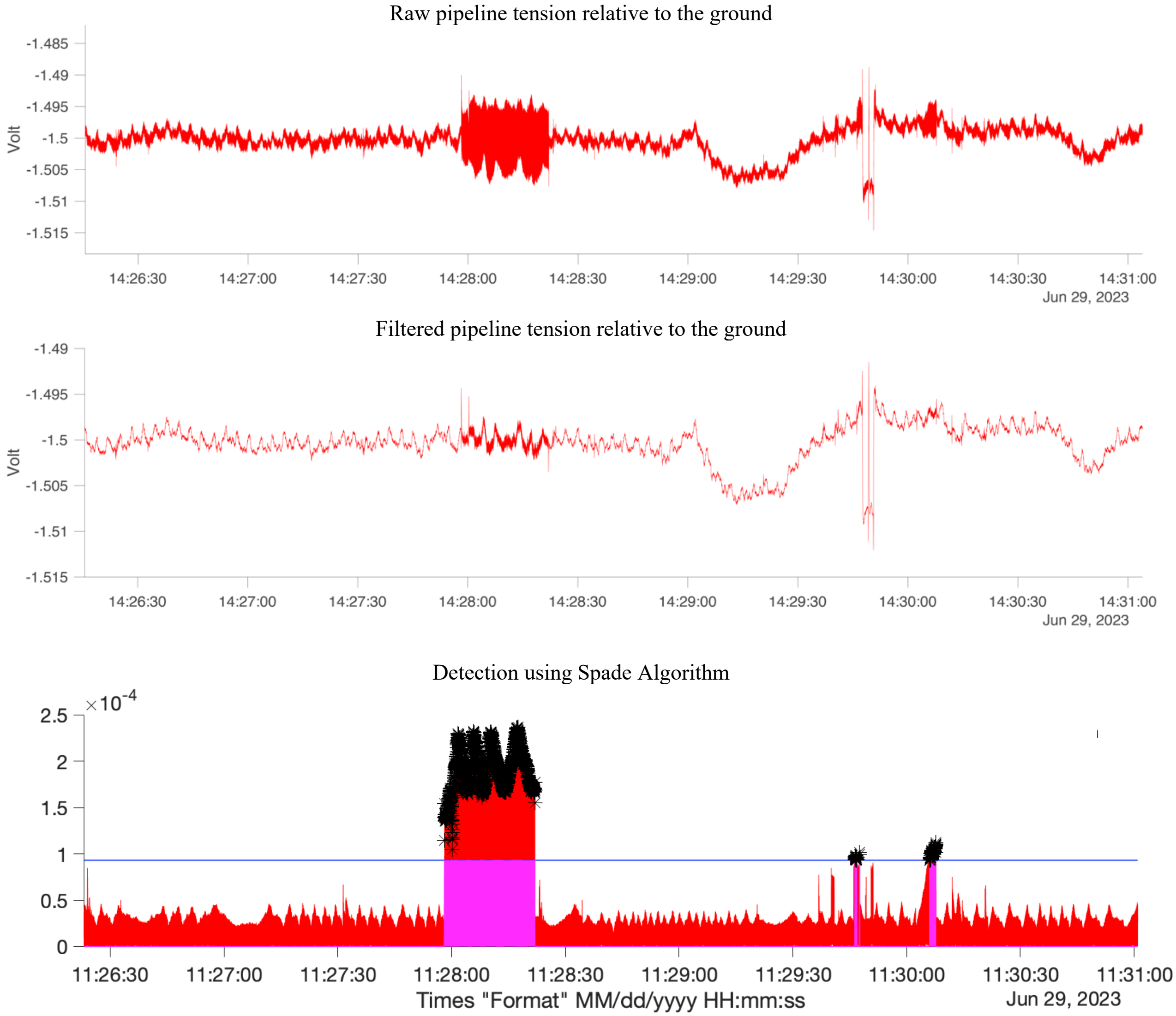


Figure 14. Signals Related to Real-time detection from 6.3 miles (9.6 km) of mechanical impact on FBE and Coal Tar Coatings

5.3.3 Task 5 – Real-Time Detection of Mechanical Impact on Pipeline with AC/DC Interference

Data presented in Figure 15 show real-time detection at 9.2 miles (14.8 km) from the point of mechanical impact on a pipeline with coal tar coating in soil of resistivity < 500 ohm.m. The environment is exposed to AC and DC interferences, generated by electric power lines and passage of the Paris-Toulouse electric train. The left graph in Figure 15 shows data from the data logger at the point of impact. The middle graph shows the same data received from 9.2 miles (14.8 km) where the SPADE and the rectifier are installed. The right graph shows the same data after processing using the SPADE algorithm. On this right graph, each × marks an instant in which the excavator impacted the pipeline.

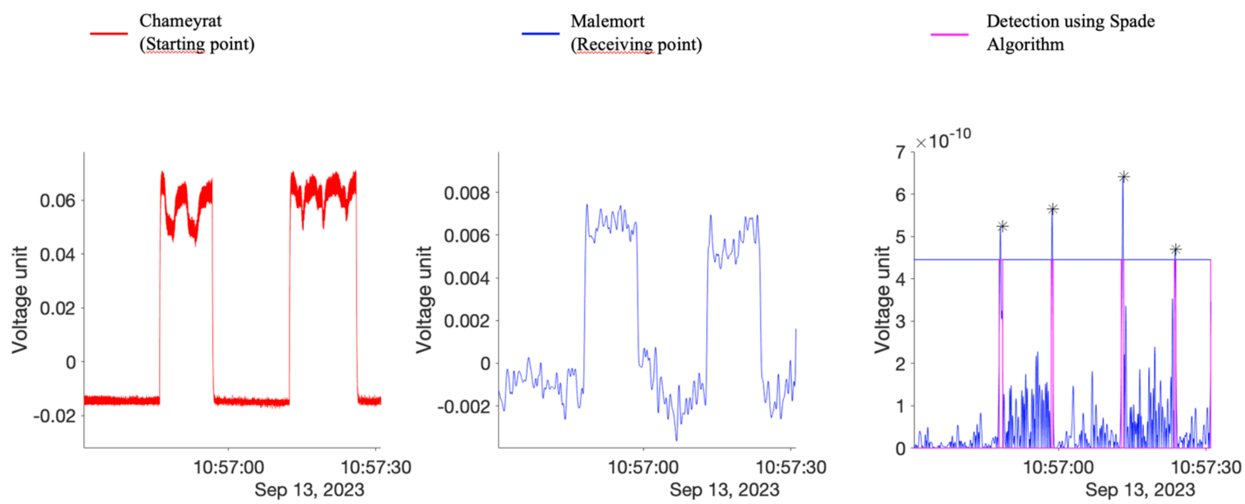


FIGURE 15. Signals Related to Real-time detection of Mechanical impact in the presence of AC/DC Interference

5.3.4 Task 8 – Real-Time Detection of Illegal Tapping

Data presented in Figure 16 show real-time detection at 6.3 miles (9.6 km) of an illegal tapping on a pipeline with coal tar coating in soil of resistivity < 500 ohm.m. The upper graph in Figure 16 shows the raw data from the data logger. The middle graph shows the same data after filtering and processing using the SPADE algorithm. On the lower graph, each × marks an instant in which the tap was welded on the pipeline.

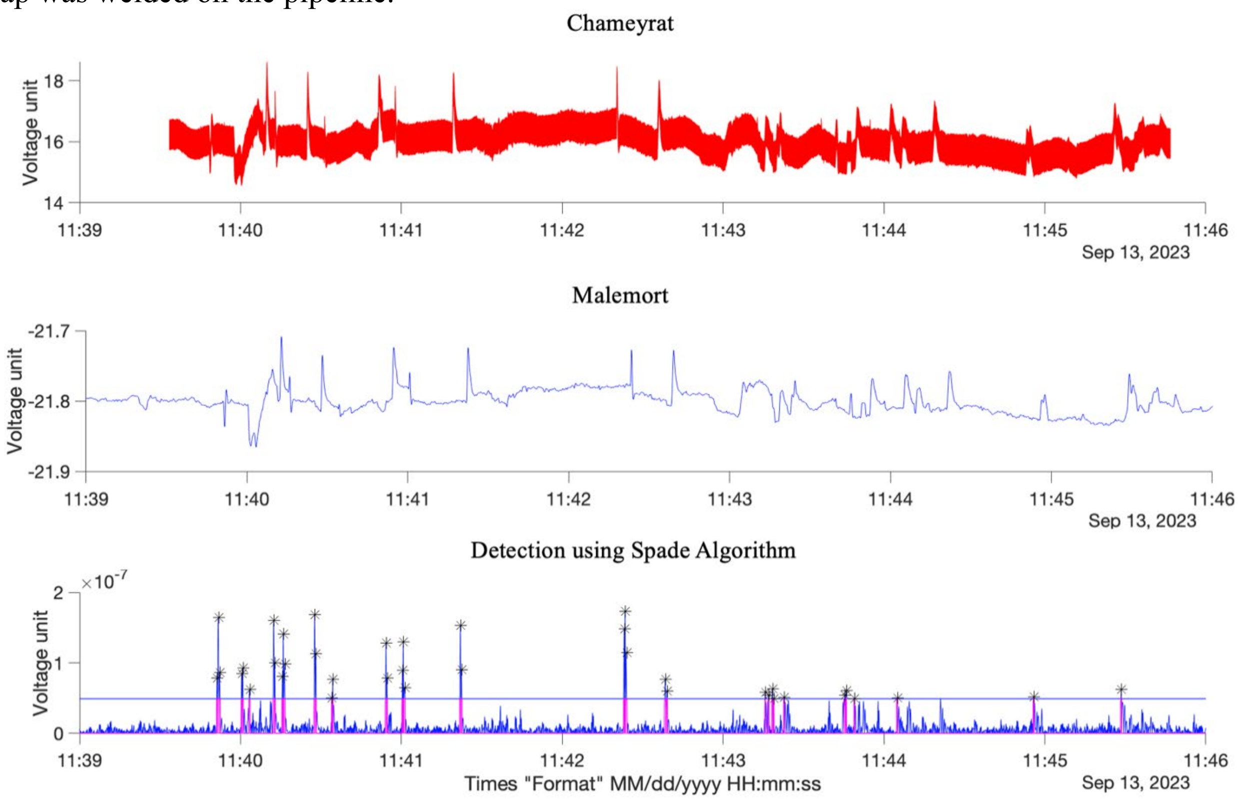


FIGURE 16. Signals of Real-time detection of Tapping

5.3.5 Task 7 – Real-Time Detection of Mechanical Impact in Soil Resistivity > 500 ohm.m

Data presented in Figure 17 show real-time detection at 4 miles (6.4 km) from the point of mechanical impact on a pipeline in soil of resistivity of 876 ohm.m. The left graph in Figure 17 shows the filtered signal at the point of impact. The middle graph shows the filtered signal received 4 miles (6.4 miles) further. The right graph shows the signal after processing using the SPADE algorithm. On this last graph, each × marks an instant in which the excavator impacted the pipeline.

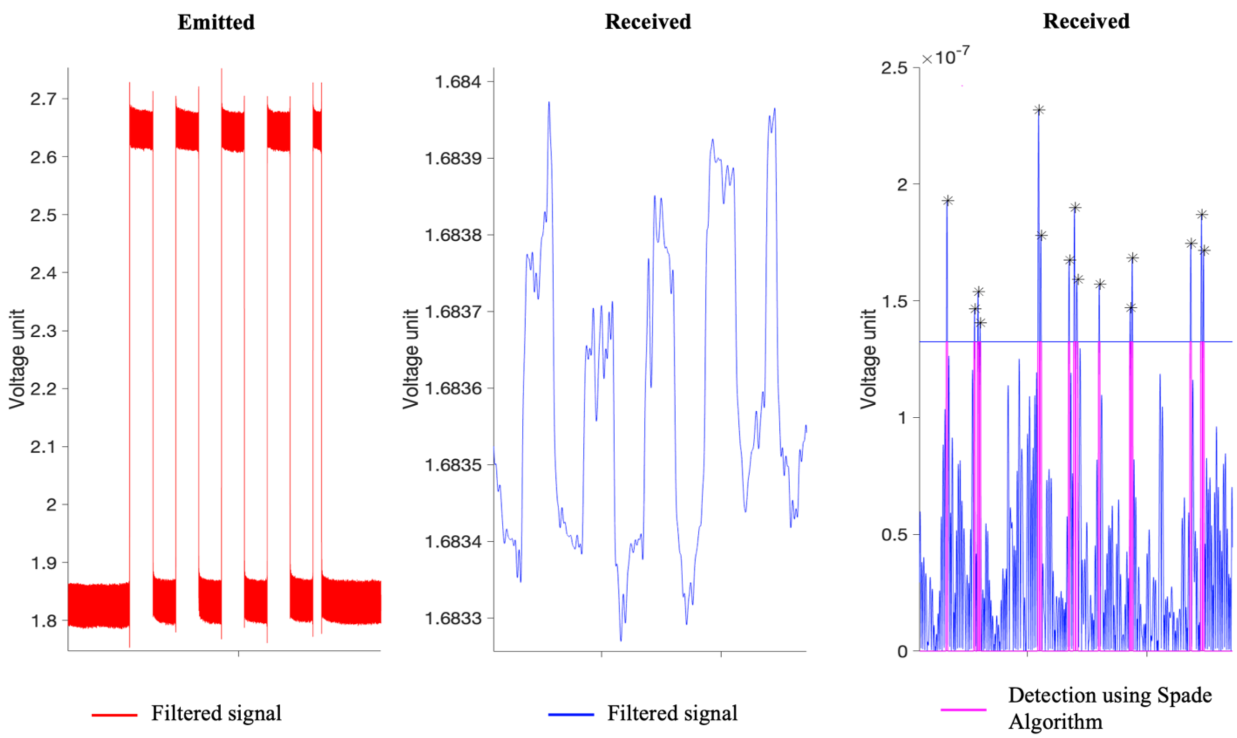


FIGURE 17. Signals of Real-time detection of Mechanical Impact in Soil Resistivity of 860 ohm.m

6 – Recommendations

Installation of SPADE in high consequence areas ensures permanent monitoring of the pipelines and real-time detection of mechanical threats.

At this stage, prior to the installation of the SPADE system, it is necessary to record for 2-3 days the electrical signals on the pipeline. The analysis of the signals would allow to minimize electrical interferences and stabilize the cathodic protection through on-site intervention, such as fine-tuning the current drainage on the network. As more field data is acquired, SPADE will be able to upgrade its algorithms to automatically filter electrical interferences at installation.

7 – Conclusions

The objective of this PRCI project is to test SPADE's performance under various configurations and terrain conditions. Based on the pilots that were conducted in the field, the following results are confirmed:

- Real-time detection of an electrical short between a pipeline and its casing from 15 miles (24 km).
- Real-time detection of an excavator's impact from 9.2 miles (14.8 km), in the presence of AC/DC interference.
- Real-time detection of pipeline tapping from 9.2 miles (14.8 km), in the presence of AC/DC interference.
- Real-time detection of an excavator's impact from 4 miles (6.4 km) in a soil resistivity of 876 ohm.m.
- During the trials, the following events could also be detected:
    - Presence of stray currents (AC/DC)
    - Lightning strikes on the pipeline

SPADE's installation did not require any modification to existing equipment on the pipelines.

8 – Acknowledgements

Special thanks to GRTgaz and PG&E for their in-kind support by authorizing to conduct the tests on their networks and providing all required human and logistical support.

The authors acknowledge helpful discussions with Dr. Winston Revie.

Carrie Greaney, the PRCI project manager, and her colleagues ensured a perfect co-ordination.

APPENDIX

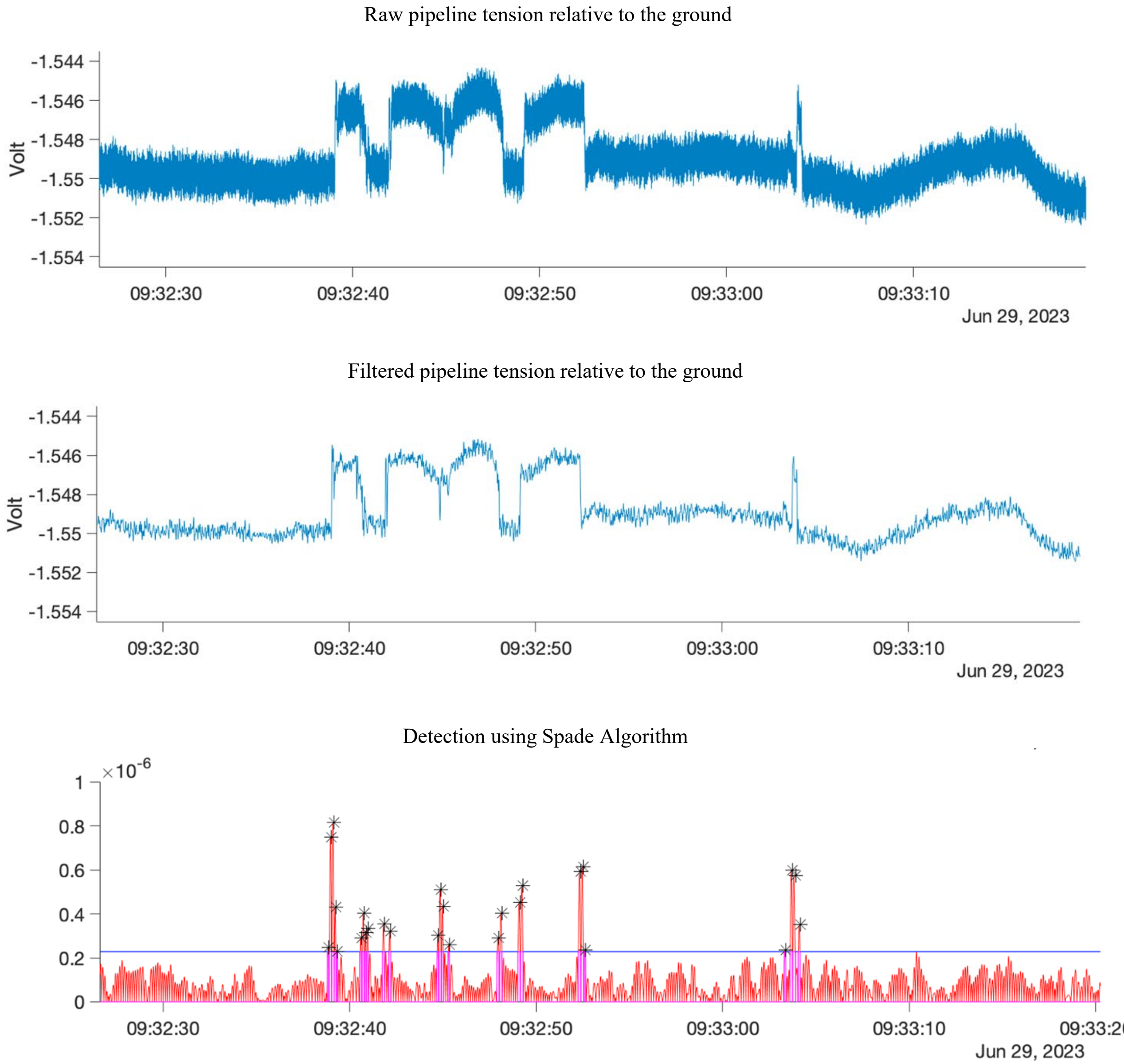
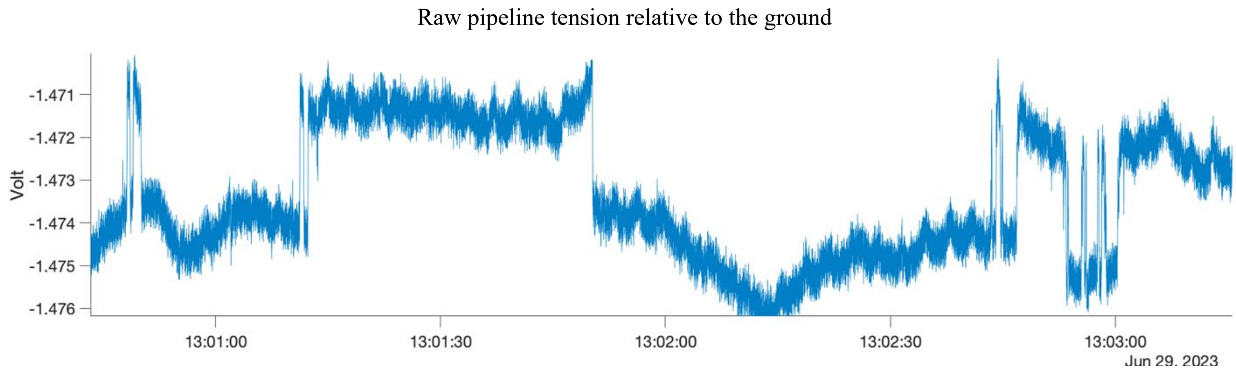
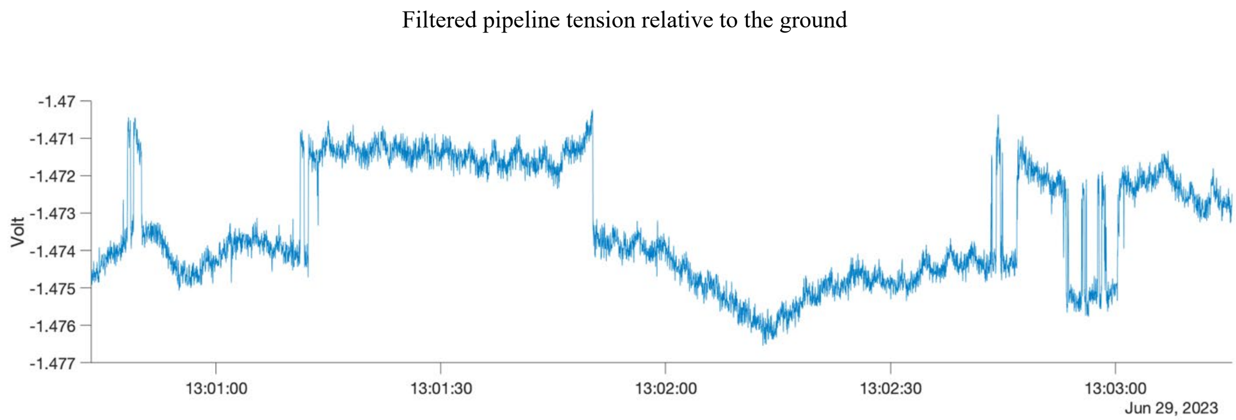


Figure A1. Real-time detection of impact on PG&E pipeline network in Hollister, California, Tasks 2, 3, 4, and 6 – Pipeline with FBE and Coal Tar Coating, Soil Resistivity < 500 ohm.m, data logger at CP test station 452.90, 1.6 miles from the point of impact





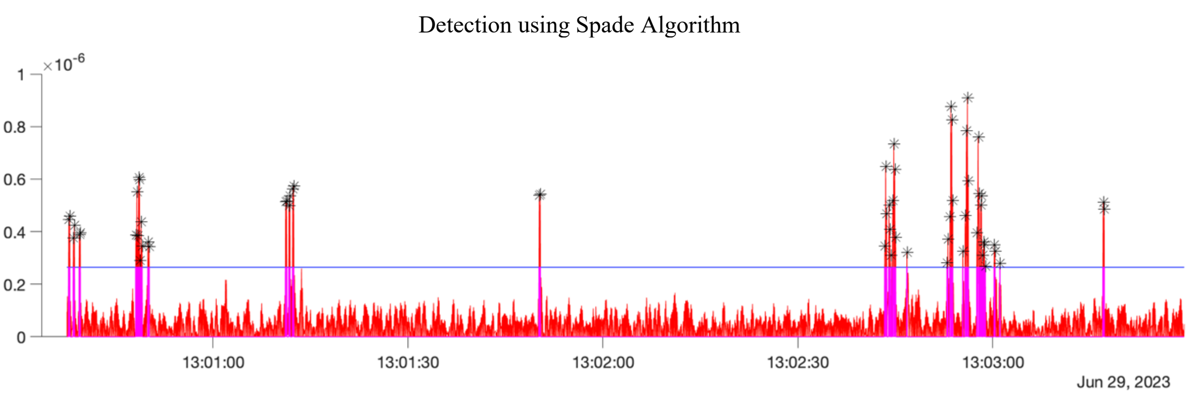


Figure A2 Real-time detection of impact on PG&E pipeline network in Hollister, California, Tasks 2, 3, 4, and 6 – Pipeline with FBE and Coal Tar Coating, Soil Resistivity < 500 ohm.m, data logger at CP test station 455.80; i.e., 4.4 miles from point of impact

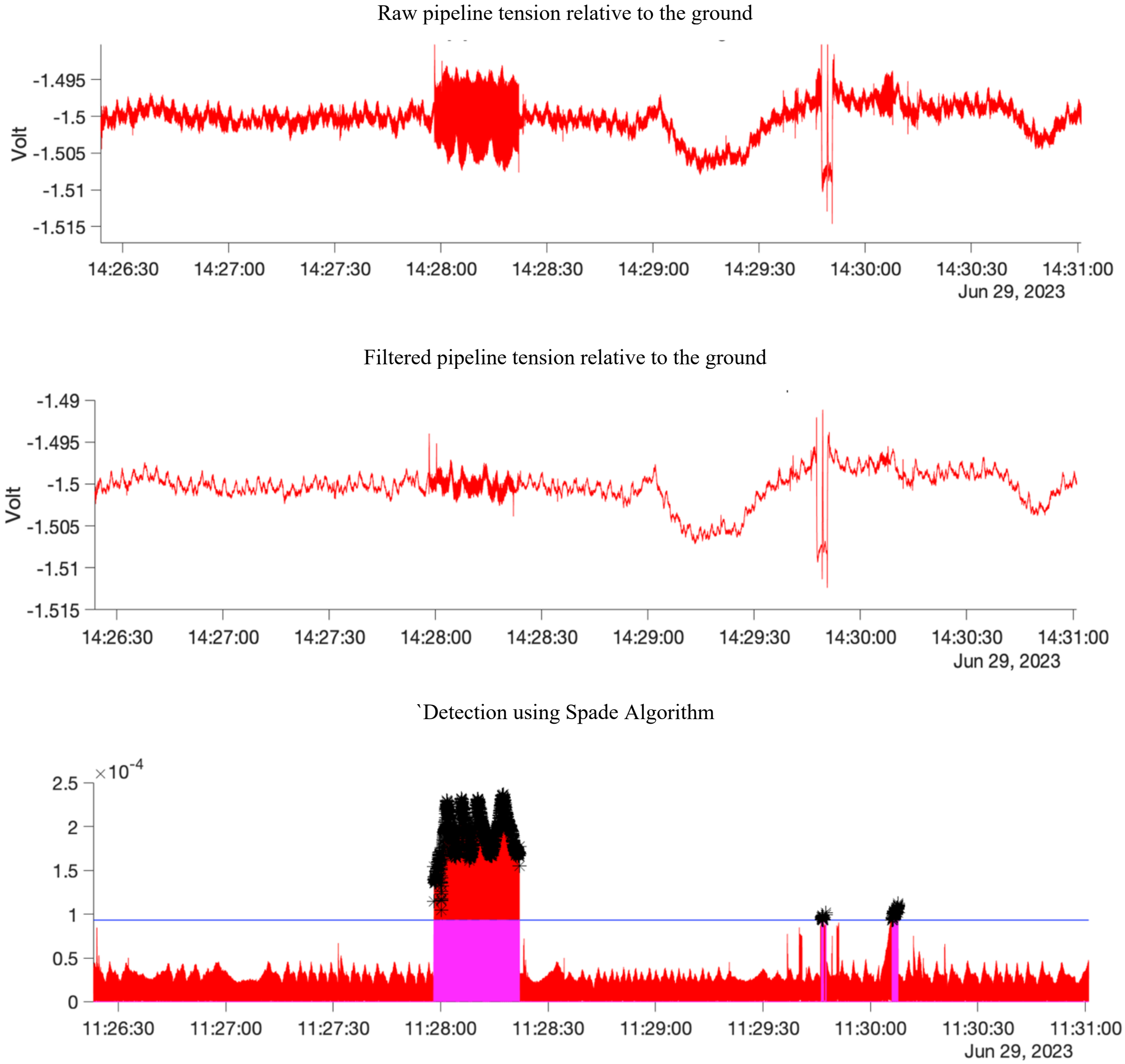


Figure A3. Real-time detection of impact on PG&E pipeline network in Hollister, California, Tasks 2, 3, 4, and 6 – Pipeline with FBE and Coal Tar Coating, Soil Resistivity < 500 ohm.m, data logger at CP test station 457.87; i.e., 6.3 miles from point of impact