Operational performance validation results for a satellite-based ROW monitoring solution

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Abstract

For the past decades, helicopter surveys have been the state-of-the-art solution for right-of-way (ROW) monitoring to protect pipelines from third-party-interferences (TPI's). When TPI activities damage a pipeline, it can lead to disastrous events. Therefore, aerial inspection early-warning systems are used to mitigate these risks. Recent developments in Earth observation (EO) technology make satellite-based ROW-monitoring a new contender as a valid TPI early-warning system.

The main drawbacks of aerial platforms relate to weather dependence, unreliability due to a low temporal re-visit rate and subjective reporting by the human observer. Nevertheless, the industry has been holding on to this technology, as it is a proven concept with a perceived high performance and is well-integrated into operations. The satellite-based system, CoSMiC-EYE (Combined-Sar-Multi-spectral-Change detection), has been developed by Orbital to overcome these weaknesses, while operating with a similar false alarm rate and providing an easy-to-use workflow. Presented in an intuitive user-interface, this solution is ready to be integrated into pipeline operators' monitoring capabilities.

In the past two years a number of studies and operational pilots were completed to compare the satellite-based solution to conventional helicopter inspections. In this conference contribution we present and detail our findings of this work which was executed together with a number of European pipeline operators. These results will show, among other valuable insights, that satellite-based ROW-monitoring can in many cases outperform traditional aerial inspections methods in terms of number of relevant detected TPI's, low false alarm rate and illustrate a proven early-warning capability.

When protecting communities, the environment and assets is the main goal of a ROW-monitoring solution, then CoSMiC-EYE is the way forward. EO-solutions no longer behold for the distant future, as the pipeline industry has been assuming. The contrary is true, a satellite-based solution is already here and is ready to become the new industry standard.

1 Introduction

Pipeline operators are responsible for the safe transmission of their products to protect communities, the environment as well as their own assets. Failures are high impact events, which can cause major damage and casualties. The foremost cause of damage to buried pipelines, together with geohazards and corrosion, is Third Party Interferences (TPI's), such as excavations, construction works or city encroachments.[1] Hence, right-of-way (ROW) monitoring solutions have been introduced over the past decades to mitigate these risks. Basically, any successful ROW-monitoring solution should demonstrate at least the following characteristics:

1. Early warning functionality: (imminent) events should be reported to the pipeline operator as soon as possible.

2. Reliability: all events that pose a risk to the pipeline should be reported to the operators with a low false alarm rate.
3. Ease of use: the technology should be simple to use and suitable to be efficiently integrated in the daily workflow of operators.

The pipeline sector currently uses manned aerial vehicles as their preferred ROW-monitoring solution. A human observer detects anomalies along the pipeline corridor, which are reported to the pipeline operators. In general, human observations from aerial platforms can be very selective resulting in a low false alarm rate, but are also subjective (different observers will report different things) and have a relatively low revisit frequency (due to high costs) causing many TPI's to be left unnoticed, as every location is only visited (bi-)weekly. Furthermore, most aerial platforms such as helicopters or drones, are not reliable under severe weather conditions. As a result, aerial platform-based monitoring solutions are, despite the low false alarm rate, far from optimal due to the low temporal frequency, subjective reporting of events and weather dependence.

Many of the shortcomings of aerial platforms can be addressed by space-born Earth Observation (EO) platforms, which are already numerously present in an orbit around earth. ROW-monitoring using satellites is no longer a mere theoretical concept, but has grown over the past couple of years into a mature and competitive technology. Hence, this technology is now in the final validation stages, preparing for widespread deployment in the pipeline industry in the coming years. This paper will present results for a number of validation campaigns, demonstrating that satellite based TPI monitoring methods are indeed a valid alternative as an early-warning ROW-monitoring solution compared to modern-day helicopter surveys.

In Section 3, the satellite-based monitoring solution CoSMiC-EYE (Combined Sar Multi-spectral Change detection), is introduced, discussing both the technology as well as its operational implementation. Next, a number of validation studies are discussed in Section 3 to show the current performance of satellite-based monitoring and compare the technology to aerial-based solutions. Then, a summary of the main conclusions is given in the discussion of Section 4 and the final Section 5 elaborates on the future of the industry and upcoming challenges.

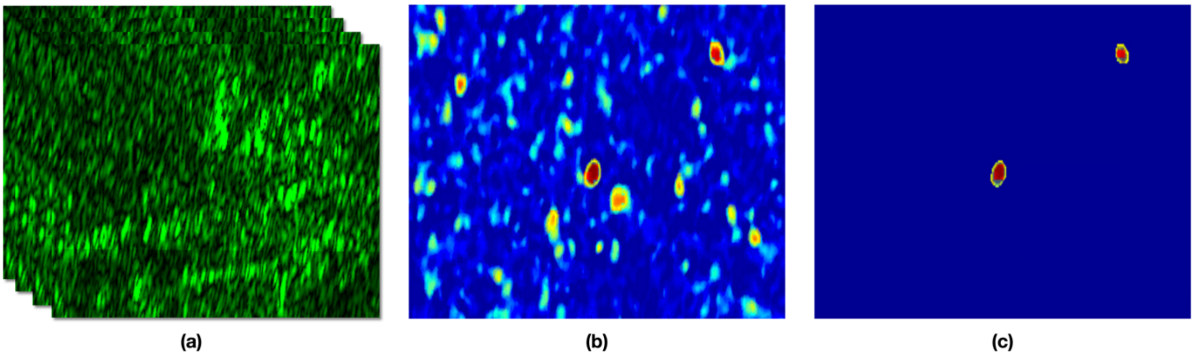
2 Background – Right-of-Way monitoring from space

The satellite-based monitoring technology discussed in this paper has been developed by Orbital Eye, a company specializing in satellite data analytics to detect and monitor activities at the earth's surface. Instead of data products, Orbital Eye offers tailored integrated solutions. In the case of TPI monitoring, pipeline inspectors and managers are basically provided with a decision support platform to detect, track and manage TPI's along their assets.

One of the challenges for satellite-based monitoring systems is the visual impediment caused by clouds. To overcome this problem, Orbital Eye's monitoring technology is based on Synthetic Aperture Radar (SAR) satellites which are unaffected by cloud cover.[2] The solution makes use of the Sentinel-1 satellite constellation which can observe most locations on Earth up to 120 times a year.[3] The average revisit interval over the whole Earth is six days. This capability to revisit pipeline routes multiple times per month, at a reduced cost compared to traditional aerial surveys, offers the possibility to intercept more potentially hazardous activities. This in turn not only reduces the risks on major incidents, but also helps in avoiding smaller damage that on the long run can result in leaks and fugitive emissions impacting the environment.

At the heart of the Orbital Eye technology is a modified SAR Coherent Change Detection algorithm that compares a stack of co-registered radar images at different capture times, as shown in Figure 1.

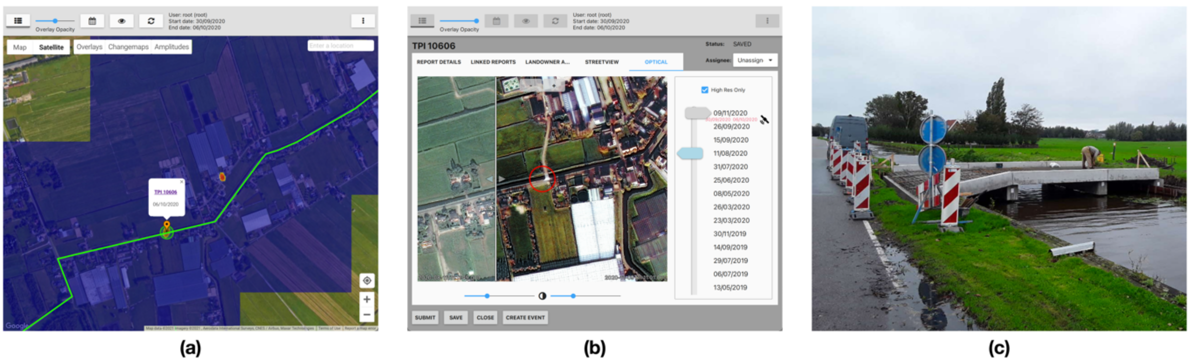
Figure 1: Overview of the three main steps that define the change detection algorithm: (a) stack of SAR images, (b) the detected changes and (c) the filtered change maps ellimating all non-threatening events.



The system acquires radar satellite images along the pipeline routes, and automatically processes and analyses these images to detect anomalies and filter irrelevant changes. For this, both classical image processing and filtering techniques are used, as well as Artificial Intelligence (AI) based filtering and classification techniques. These filters have been developed, calibrated and trained using the vast amounts of 'ground truth data' collected during the past five years of pilots and operational campaigns to offer the best possible detection performance. In this way, activities undertaken or caused by humans, which pose the largest threat to the pipeline – such as excavations, illegal settlements and landslides – are retained and reported.

Once anomalies are detected within the pipeline corridor, the software generates a radar alert which is reported to the client through a notification (see Figure 2). In addition to using radar data, the software integrates all relevant geographical information in its servers, which can be displayed in the user interface of the client application. As a result, the pipeline inspectors can obtain a complete overview of all detected TPI's in the ROW, whether reported by radar satellites, aerial platforms, field patrols or wayleave notifications, giving them optimal situational awareness of all activities in and near their ROW.

Figure 2: Detection and follow-up of a TPI: (a) a detected anomaly is shown on the map interfering with the pipeline corridor, (b) using high-resolution optical data the location of the TPI can be analyzed and (c) a field inspection is done to verify the activity and take mitigating measures when appropriate.



As the radar alerts do not provide visual interpretable information, optical satellites can be automatically tasked to collect imagery for the locations around the radar alert. These enable the pipeline operator to classify the type of TPI from the office and reduces the number of follow-ups in the field. This additional capability is achieved via a completely machine-to-machine integration with the EarthCache platform of SkyWatch[4], which is a fully automated solution connecting service providers with satellite data repositories. This platform provides the most appropriate high-resolution optical imagery available within the timeframe required, therefore ensuring fast delivery of optical satellite imagery that is needed for ROW-monitoring purposes.

The Orbital Eye data service for ROW-monitoring thus offers an early-warning system based on smart data fusion of satellite data and geographical information that enables pipeline inspectors to prioritize and organize their field inspection tasks.

3 Historic and operational studies

In the past two years, multiple studies were performed to validate the satellite-based solution in an operational environment. During the first year, three transportation networks were monitored for a few months each. When the studies came to an end, the observed interferences were analyzed in an historic study, which highlighted a number of further improvements of the system to make it truly fit to be rolled out as an operational ROW-monitoring solution. These historical studies are discussed in Section 3.1. Next, the improvements were applied and three new studies were performed during the second year. Section 3.2 discusses the results of the study for two transportation pipelines and one dense distribution network. These results come straight from the field operators and present the latest operational performance of a space-born ROW-monitoring solution. Where available, the satellite-based solution was also measured against helicopter inspections to set a benchmark and compare the performance of both solutions. The comparison to the helicopter inspections is presented in Section 3.3.

3.1 Historical studies

The first set of studies were performed in The Netherlands and Germany and are summarized in Table 1. One of the studies was conducted with the largest DSO of Germany, Westnetz. The monitored areas covered a variety of land usages from rural regions to dense urban and industrial areas, such as the port of Rotterdam and the Ruhr Area. The combination of these different land uses makes the outcome of these studies representative for most transportation and distribution networks in the world. Hence, the observed performance should be generally applicable to most pipeline operators.

Table 1: Overview of the main characteristics of the three historical studies.

	Study 1	**Study 2**	**Study 3**
Country	Germany	Germany	Netherlands
Type	Transport	Transport	Transport
Area class	Rural/Urban	Dense Urban	Industrial/Urban/Rural
Pipeline length (km)	170	33	606
Corridor width either side (m)	20	15	15
Duration (months	4	12	3
Anomalies/month	2.8/100km	5.6/100km	2.9/100km

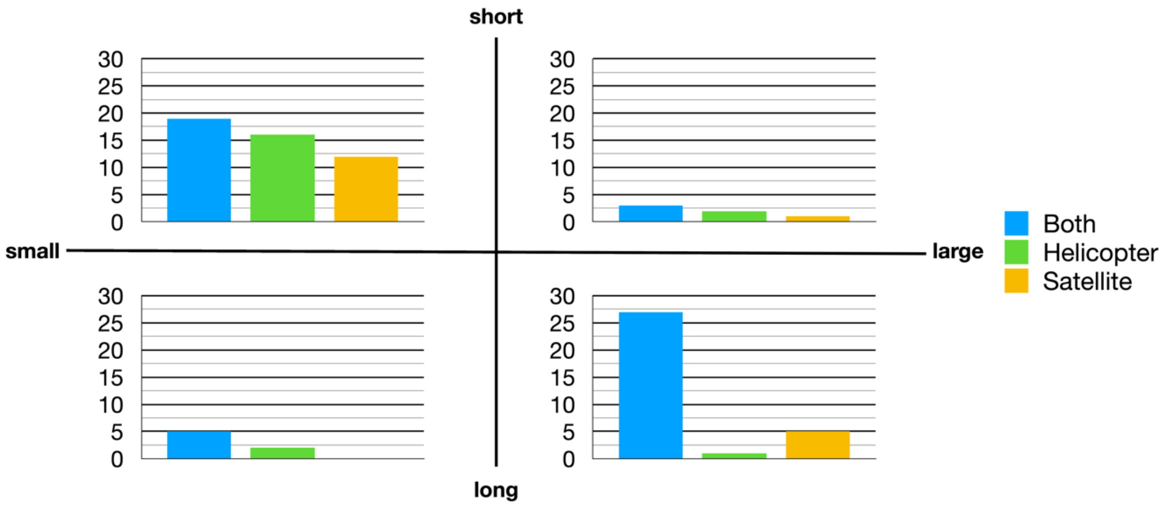
The results discuss all reported activities for the duration of each study that could pose a threat to the pipelines, such as: construction, demolition or ground works. Furthermore, the identified activities were divided into four different categories based on size and duration of the works:

1. Small events are at maximum ~50m^2, have at most a few vehicles and little to no heavy equipment on site.
2. Large events are over ~50m^2 and are characterized by heavy equipment.
3. Short duration activities are generally lasting up to a couple of days.
4. Long duration activities take around a week or longer to complete.

The combined results of all three studies are shown in Figure 3. The number of identified activities is shown for all four categories. Furthermore, the events identified by the helicopter, the satellite or both systems simultaneously are shown separately.

Figure 3 clearly shows that most events taking place within the pipeline corridor consist of small and short-lived events that are shown to have a similar probability of detection for both the helicopter as well as the satellite. Despite the low visit rate (i.e. bi-weekly) the helicopter is able to detect a bit more of the smaller events due to the human observer, who can easily spot small (signs of) works at a low flight altitude. On the other hand, the satellite-based solution has a slightly lower sensitivity, but compensates this by a higher chance of detecting short lived events due to its higher re-visit rate (i.e. at maximum 3 days in Western Europe).

Figure 3: Combined overview of the detected events during three historical studies using the helicopter and satellite, which are divided into four categories based on size and duration of the works.



Furthermore, the second category of most common events are the large and long-lived works. Almost all of these events involve ground disturbance. Also, the use of heavy equipment makes this type of event a likely threat to any buried pipeline. The satellite as well as the helicopter are very capable in detecting this type of events. Overall, the satellites-based solution was able to detect more large events compared to the helicopter, which mainly occurred in dense urban areas. This can most likely be explained by the fact that it is more difficult for a human observer to keep track of recent activities within a bigger working site. The observer is basically making spot observations, whereas the satellite-based system is detecting changes (comparing the current state with that of the previous cycle) allowing it to more consistently flag this type of activities. It should be noted here that there is a need for optical imagery to classify activities detected by the satellite. When no optical imagery is available, the number of false alarms can double, which will be discussed in more detail in Section 3.3.

3.2 Operational pilots

During 2020 three studies were performed in an operational setting. The obtained results reflect the follow-up of all detected interferences by the field operators. Separate results are presented for the transportation and distribution networks in respectively Section 3.2.1 and 3.2.2. Both transportation networks were monitored in the Netherlands and the distribution network was distributed over multiple dense urban areas in France. An overview of all three studies is shown in Table 2.

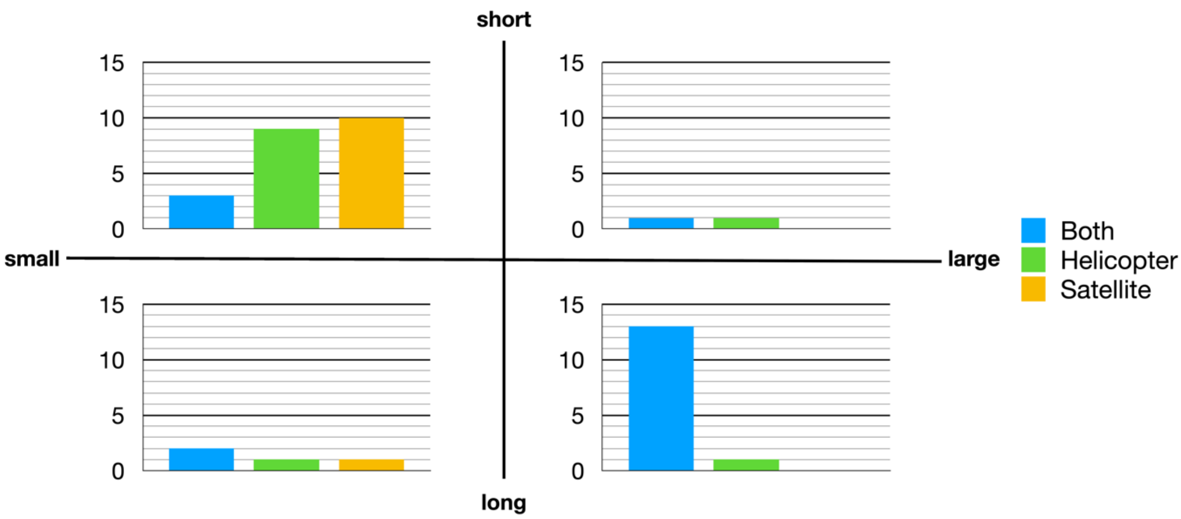
Table 2: Overview of the main characteristics of the three operational studies.

	Pilot 1	Pilot 2	Pilot 3
Country	Netherlands, Belgium	Netherlands	France
Type	Transport	Transport	Distribution
Area class	Industrial/Urban/Rural	Industrial/Rural	Dense Urban
Size	208 km	130 km	45 km^2
Corridor width either side (m)	30	15	15
Duration (months	2	3.5	2.5
Anomalies/month	10.1/100km	11.1/100km	5.3/10km^2

3.2.1 Transportation networks

The TPI's reported during Pilot 1 were effectively based on only radar data for a network over 200 kilometers during 2 months. All identified works are shown in Figure 4.

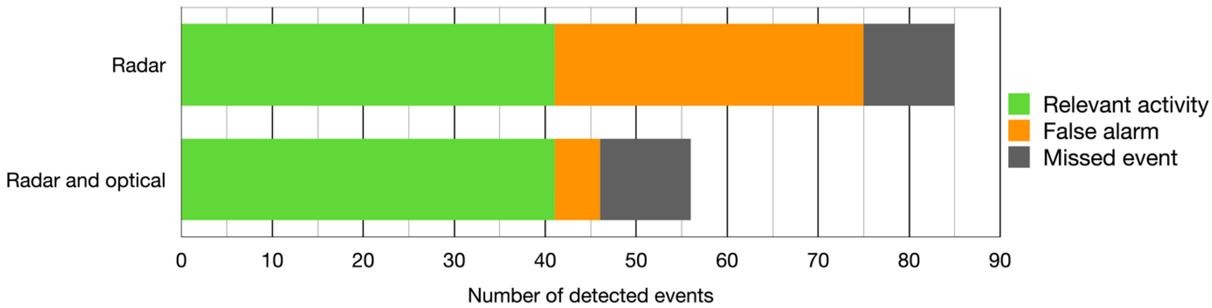
Figure 4: Combined overview of the detected events during first operational study of a transportation pipeline using the helicopter and satellite-based solution, which are divided into four categories based on size and duration of the works.



These results are very comparable to the historic studies of Section 3.1. An interesting remark is the ratio of small short-lived events detected by either system. Both systems were able to detected most small short-lived events simultaneously during the historical studies. While the helicopter and satellite detect different events at a similar rate during the first operational Pilot, the improvements of the algorithms based on the historical studies have increased the detection rates of the satellite-based solution and proof that the system can compete with the helicopter during an operational pilot.

The second operational Pilot took place in the Netherlands and focused on the effect of optical imagery on the false alarm rate. Nine inspection rounds were carried out at a twelve-day interval. All reported locations were visited and classified in the field, which also gave the opportunity to report any missed events. The results are shown in Figure 5 and clearly show the impact of optical data on the false alarm rate. The false alarm rate goes down from 45% to 11%, which is a highly significant improvement and makes the satellite-based ROW-monitoring a suitable operational system.

Figure 5: Number of detected events by the satellite during the second operational study of a transportation pipeline. Results for the same pipeline are presented for a system that reports solely based on the radar and a system that also integrates optical data.



3.2.2 Distribution networks

The last operational Pilot took place in France and covered a distribution network of 45 km^2 for 2.5 months. The satellite solution was configured to only report events based on the radar, when there were also recent optical images available to identify any ongoing activities. This setup is especially important in busy urban areas that are continuously changing. If this measure is not put into place, then a change detection-based system is prone to a high false alarm rate. The additional optical imagery had the goal to support the pipeline operators and provide detailed information to the system with the goal to have a minimal false alarm rate. Note that distribution networks are typically not monitored using aerial inspections, thus reporting only TPI's when there is optical data available for verification, is still a big step forward in keeping also these class of pipeline networks safe.

To illustrate the need for optical imagery in dense urban settings, two examples in an urban setting are shown in Figure 6 and Figure 7. Figure 6 shows a potential threat next to a road that was detected by the satellite. Additional analysis of the location using an optical image before and during the event (Figure 6a and Figure 6b) shows that an excavation next to the road is taking place, that otherwise could have been mistakenly classified as a regular traffic activity. The optical images immediately show and prove their purpose.

A detection is shown in Figure 7. The radar signal has similar characteristics to the event of Figure 6. However, the optical images of Figure 7a and Figure 7b show that nothing is going on. The satellite-based system detected most likely a traffic related incident, which can be discarded after comparison of the optical images at the location of interest.

Figure 8 shows the result that were collected during the pilot of the distribution network. No aerial surveying platform was available to validate the results of the satellite-based system. Therefore, all reported activities are shown with their classification to showcase the performance.

Figure 6: Example of a true positive detection by the satellite in an urban environment, where the optical images before (a) and during the event (b) validate the detected change (c) between these instances in time.

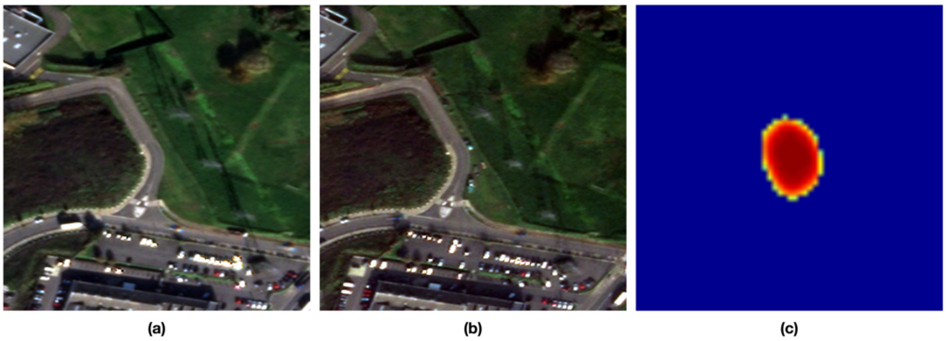


Figure 7: Example of a false positive detection by the satellite in an urban environment, where the optical images before (a) and after (b) the detected change (c) does not show any signs of an activity.

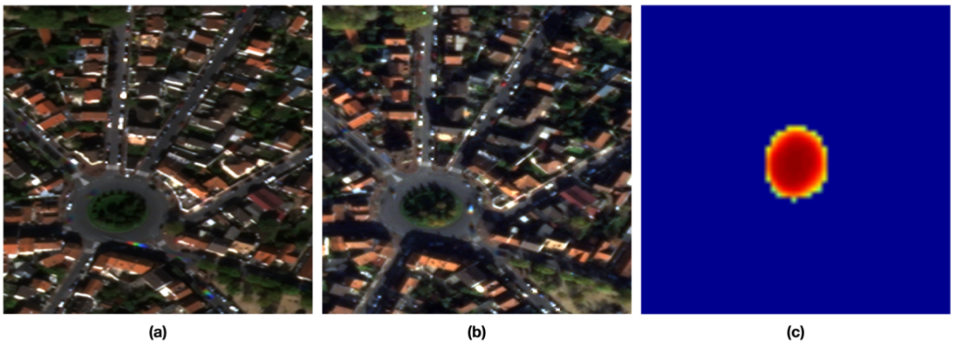
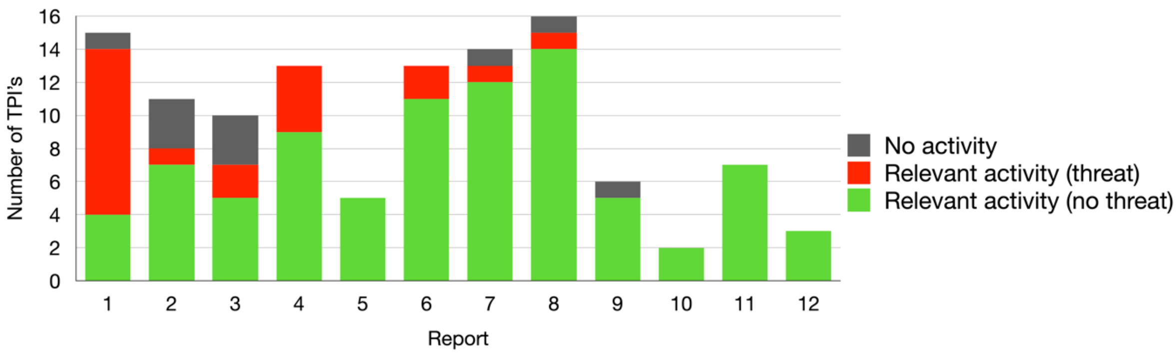


Figure 8: Detected events during the operational pilot of a distribution network. The number of reported activities is shown per inspection round at an interval of 6 days. All reports were followed-up and classified based on their relevancy to the pipeline operators. Threats are events that were unknown to the field operators or activities that did not meet regulations or protocols.

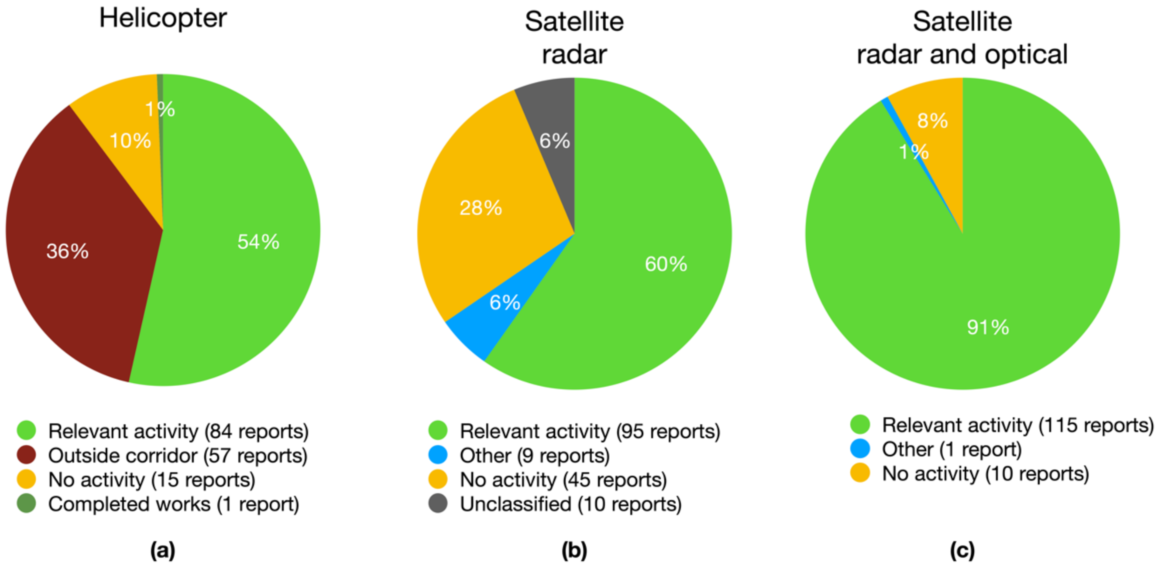


The number of reported activities per round is a function based on the availability of optical data, as this is a prerequisite in order to report a TPI. However, when more optical data becomes available, then any potentially relevant events can still be reported in successive rounds. Overall, almost all reported activities are relevant and false alarms rarely occurred.

3.3 Satellite vs. helicopter

Four of the studies and pilots presented above, were executed next to an existing helicopter service. The statistics of the helicopter platform were already used to quantify the number of missed events and overlapping reports in comparison to satellite based solution. The same data is used once more to compare the individual performance of the helicopter to the satellite-based solutions with and without additional optical imagery. Figure 9 shows the true and false positive ratio of each monitoring solution tested in the past 2 years.

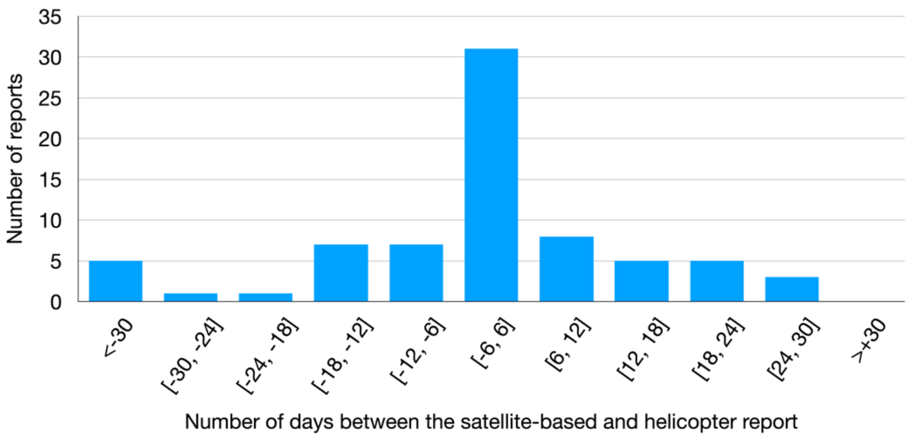
Figure 9: Overview of the true positive and false positive ratio for three monitoring solutions: (a) the helicopter, (b) satellite reporting based on radar and (c) satellite reporting based on radar and optical data.



The results are probably surprising to most pipeline operators, because the helicopter has a true positive ratio only slightly above 50 percent. The main drawback of the helicopter are the reports outside the corridor, which do not pose a threat the monitored pipeline. The false alarms of the satellite solutions are dominated by locations that do not show any relevant activity, the main causes being: agricultural activities, traffic, storage or parking. Comparing Figure 9b and c shows the impact of the optical imagery, which reduces the number of false alarms by 70%, because the sources of false positives, such as traffic or agricultural activities, can be observed in the optical data and prevented. As a result, the satellite solution can significantly outperform the helicopter, when optical data is correctly integrated.

Furthermore, the reporting time of the satellite solution was compared to the helicopter based on the locations that were reported by both systems simultaneously. The results are shown in Figure 10 and compare the satellite solution to the helicopter.

Figure 10: Overview of the difference in reporting time by the satellite in comparison to the helicopter in intervals of 6 days, where the helicopter is used as the baseline and reports at day 0.



The helicopter reports are used as the baseline and report on day=0. The Sentinel 1 satellites used by the satellite solution have a repeating orbit of 6 days, hence the results are grouped in 6-day intervals. Based on the results of Figure 10, it becomes clear that both systems on average report within 6 days of each other. In other words, when the helicopter reports a work, then the satellite solution reports it as well during the previous or next cycle that the satellite passes.

3.4 Summary

A summary of the results from the analysis between the helicopter and the satellite-based solution is shown in Table 3.

Table 3: Overview of the main findings based on the performed historic and operational studies

	Performance	**Comments**
Historical Performance Analysis		
Detection of short and small events	Equal performance	- satellite solution observes more frequent - Helicopter is able to detect smaller events.
Detection of long and large events	Satellite performs better	- These events pose the largest threats to damage pipelines.
Operational Performance Analysis		
Detection of short and small events	Equal performance	- Systems report different events within the corridor at equal rates.
Detection of long and large events	Equal performance	- Most important threats detected by both systems.
False alarm rate	Equal or better performance by satellite	- Similar false alarm rate for both systems if satellite only uses radar data - Satellite performance better than the helicopter, if also high-resolution optical data is available
Comparison between satellite and helicopter		
False alarm rate	Satellite performs better	- False alarms of satellite are more difficult to deal with then aerial inspection false alarms (when no optical is available)
Reporting time	Equal performance	- The helicopter and satellite report on average within the next overpass of either system.

4 Conclusion

The satellite-based solution developed by Orbital Eye is highly competitive compared to modern helicopter surveys when it comes to ROW-monitoring. The satellite technology was validated against the helicopter in numerous studies and pilots over the past two years and showcased equal and sometimes an improved performance over the detections of the aerial platform. As this solution is presented in an easy-to-use interface, both for mobile devices and desktop, it can easily be integrated into pipeline operators' monitoring processes.

Three historic studies showed the potential of the satellite solution. Analysis of the large long-lasting events showed that it could even outperform the helicopter, when it came to the detection of large long-lasting works that pose the largest threat to buried pipelines. Just as interesting is the equal performance of both systems when it comes to the detection of small and short-lasting events. One may assume that the helicopter would easily trump a satellite-based system, because the human observer can spot (signs of) smaller works at low flight altitude compared to the lower sensor resolution of satellites. However, the high re-visit rate of the satellite enables these solutions to compete with the human observer even when it came to these small and short-lived working sites.

Furthermore, an additional three pilots were carried out in an operational framework. The results of these pilots reflect the classification of the field operators for all activities reported by the satellite-based solution. When compared to the helicopter, again equal performance was shown for large as well as small events. These studies also highlighted the importance of recent optical imagery for the satellite solution. The optical images are necessary to maintain a low false alarm rate in busy urban areas. Two of the pilots showed that the integration of optical data, together with the radar-based detection technology, results in a system that truly offers an operationally viable solution.

Finally, the results of all studies were combined to compare the overall statistics of the helicopter to satellite. The true to false positive ratios were computed and the early warning function of both systems was tested. False alarms were reported in 1 out of 3 cases by the helicopter, where the majority of false alarms pertained to activities outside the pipeline corridor. Similarly, 1 in 3 of the locations reported by the satellite solution did not contain a relevant activity and were mainly caused by traffic, storage or agricultural activities. It was proven that this false alarm rate could drop to ~10%, when recent optical imagery was available for all detected events. In addition to the false alarm rate, the early warning function of both platforms showed equal performance for both the satellite and aerial based solutions. Therefore, it was illustrated that satellite-based ROW-monitoring solutions can report relevant TPI's with a similar performance and as time accurate as modern helicopter surveys.

In conclusion, the studies carried out over the past years do not only show the potential of the satellite-based monitoring technology, but also indicate that it can already compete operationally with the helicopter at similar or even lower costs. The strength of the satellite-based system comes from the high visit-rate (i.e. 3 days) and the innovative combination of radar and optical satellites. This combination also makes the system highly reliable as a monitoring service, as the system can always report with basic performance regardless of weather and improves over existing methods when weather allows collection of optical imagery. When protecting communities, the environment and assets are the main goal of a ROW-monitoring solution, then satellite-based technology of is the way forward. EO-solutions no longer behold for the distant future, as the pipeline industry has been assuming. The contrary is true, as a satellite-based solution is already here and can compete to become the industry's latest standard.

5 Future challenges

The results of the studies and pilots show that a satellite-based solution can actively compete with modern-day helicopter surveys. At the moment multiple large-scale operational campaigns have been started or are continuing in- and outside Europe. The initial results again confirm the findings presented in this paper; however multiple challenges remain to be solved in the coming years. For example, the lack or varying quality of optical data results in a challenge that directly ties into the acceptation of the technology by the users of the satellite solution. This in part will be solved by the rapid developments observed in the earth observation sector, where the number of high-quality satellites is growing rapidly increasing both the availability of this data as well as reduce the costs. Nevertheless, the main challenge remains to gain the trust of users in this industry, who relied for so long on aerial platforms. They have to be made familiar with EO data, learn to appreciate its advantages and deal with its specific challenges before they can put their trust in a satellite-based solution.

Furthermore, the false alarm rate of current aerial surveillance methods has been shown to be equal to satellites, however hands-on experience shows a different perception. The fact that false alarms are typically caused by different sources, makes that the users initially express a reduced working experience for space-based systems. Conventional methods (i) mainly report events outside the ROW corridor and (ii) events that do not pose a threat, while satellite-based systems are more likely to reports locations where apparently nothing seems to happen. This makes that it is easier to trust the helicopter system for a field operator and classify a false alarm outside the corridor, than to visit a false alarm of the satellite solution where nothing is taking place. Understandably it is difficult to determine the cause of no activity, as a field operator does not know what to look for on-site when following up such a false alarm. This may alter their experience from an operational point of view. However, the main takeaway should be that the false alarm rate is similar, as well as the overall workload for both the helicopter and satellite-based solution.

Finally, missed events are the other key performance indicator that determine the value of ROW-monitoring technology. The current inspection methods miss events at a similar rate as satellite solutions, which are mainly short-lived events that don't use heavy equipment. All large intrusive works are detected by both systems, which drives the performance of either system. Although performance is measured to be equal, the market perception is different as existing methods are labelled as the golden standard. Any event detected by a helicopter and missed by the satellite solution has a greater impact on the experience compared to the other way around. Changing this mindset will take time, but will certainly happen. Especially since the technology behind the satellite solutions are still improving strongly every year and at the same time aerial platforms are facing more regulatory limitations and do not show much room for improvement anymore.

6 References

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