# Tracking shifting estuaries with remote sensing techniques to aid lifeboat rescue services

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## ABSTRACT

In certain areas of the world with large tidal ranges, rain and wind can cause the path of channels and estuaries to shift dramatically. Lifeboat rescue services must navigate through these areas in spite of the dangers it can entail. This work investigates the alternatives to provide regular mapping of the seabed, enabling these teams to reach casualties without becoming casualties themselves. Underwater Vehicles, SONAR systems and Unmanned Aerial Vehicles are all considered viable options but satellites equipped with synthetic aperture radar are proven to be the most advantageous. To map the path of the estuary, images must be taken during low tide, therefore, data availability is assessed by studying the revisit time and matching this to the tidal status of the area of interest. Different satellite options are examined, including commercial and non-commercial but a specific focus is given to Sentinel-1 due to its free accessibility. The periodicity of the satellite coupled with the tidal behaviour causes intervals during the month where no usable images can be taken. The maximum number of days between consecutive useful images is found to be 12, with an average of 6 useful images per month. The periods where these intervals happen are also identified. Therefore, to meet the user needs, an auxiliary system must be implemented to assist the satellite and increase the number of useful images taken per month. The area of interest of this study is the Solway Firth due to its fast tidal movements and ranges.

**Keywords:** Ocean sensing techniques, coastal features, synthetic aperture radar

## 1. INTRODUCTION

In regions characterised by large tidal ranges, the combined forces of rain and wind can trigger significant shifts in channels and estuaries. This phenomenon is extremely dangerous, in particular for lifeboat rescue services since they have to navigate these regions frequently and at high speed. In order to gain better understanding of vital information about safe routes, the volunteers are left with no alternative but to manually conduct depth soundings. Unfortunately, this task not only has to be planned and executed carefully in order to protect lives due to its unsafe and labour-intensive nature, but during bad weather and strong tidal periods these passageways shift rapidly, making the previously measured route futile. Relying on outdated routes proves to be an extremely hazardous practice, as inaccurate information can force mid-rescue course corrections or, in the worst-case scenario, even put the rescue team at risk by potentially grounding the lifeboat.

The Nith Inshore Rescue independent lifeboat service[*], responsible for the North East Solway, island rivers and lochs, confronts the aforementioned challenges on a regular basis. Having to navigate these areas rapidly and safely, the team requires an updated route of the estuaries before they set to sea, ideally requiring a complete map of the area in question once to twice per week.

Past research has effectively employed synthetic aperture radar (SAR) data obtained from satellites to precisely map dynamic estuarine environments within regions marked by substantial tidal variations.[1] While both

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[*] https://www.nithrescue.org.uk/

visual and SAR imagery have proven successful in this regard, SAR imagery offers a distinct advantage: its capability to penetrate cloud cover. This attribute assumes particular significance in areas prone to cloud formations, such as the Solway Firth, thereby conferring heightened utility to SAR-based analysis.

While recognising that prior work[1] shows SAR to be a highly promising option to map dynamics estuaries, the primary objective of this work is to formalise a set of requirements for estuary mapping, particularly for lifeboat services, and to assess a variety of technical alternatives against these requirements. Through this, we hope to ensure that the most suitable solution for this critical work is identified, and perhaps inspire further technical development of the most promising techniques. To accomplish this, the trial site chosen is the Solway Firth, which is renowned as one of the most treacherous bodies of water in Great Britain, primarily due to its propensity for dangerous and rapidly shifting channels. As part of the assessment process, a set of user needs have been developed in conjunction with Nith Inshore Rescue; these are presented in Table 1. A selection of possible mapping methods will be evaluated and compared with these requirements to determine their suitability for mapping dynamic estuary regions, such as the Solway Firth (section 2). The most appropriate option will then be evaluated in more detail (section 3) to determine its suitability and expected availability (section 4).

Table 1: User Needs

| ID | Description |
|---|---|
| U1 | The rescue team needs a system that will track the constantly shifting estuaries. |
| U2 | The system will map a route to provide a safe passage to travel through without running aground. |
| U3 | The system will provide the route frequently enough to capture the estuary shifting. |
| U4 | The system must map the whole Nith Estuary. |
| U5 | The route will be provided before the crew sets out. |
| U6 | The system will need little to no manual intervention. |
| U7 | The system must possess the capability to capture images even during adverse weather conditions. |

## 2. REVIEW OF MAPPING METHODS

### 2.1 Autonomous Underwater Vehicles

Autonomous Underwater Vehicles (AUVs) represent a transformative force in marine exploration, yet they are governed by distinct operational constraints that demand meticulous consideration. A pivotal parameter is the velocity of ocean currents, with the Solway Firth serving as a pertinent example. This coastal area experiences robust tidal currents, reaching up to 4 knots (2.05 m/s) during spring tides and 2 knots (1.03 m/s) during neap tides.[2] Significantly, AUVs commonly deployed for marine geoscience operate within the speed range of 1.5 to 2 m/s.[3]

Difficulty arises when current speed approaches or surpasses the AUV's operational pace, compromising precision and risking potential vehicle loss. Comparison of the Solway Firth's maximum tidal current velocity against the AUV's peak functional speed reveals an unsettling reality - heightened tidal activity days render the AUV susceptible to the Firth's formidable currents, raising loss concerns. Furthermore, specialised training is needed to adeptly manipulate and navigate AUVs. This training is labour-intensive, necessitating resource allocation alongside additional costs. This combination of current velocity restrictions and human skill requirements poses a significant challenge in harnessing AUVs for intricate underwater missions.

### 2.2 Remotely Operated Vehicles

Remotely Operated Vehicles (ROVs) are sophisticated underwater devices designed for meticulous exploration of vast aquatic domains. Fitted with advanced instruments like high-resolution cameras and precision sonars for seabed mapping, these mechanised agents establish a real-time link to surface vessels through intricate cable networks. This requirement to tether ROVs to a surface vessel poses a pivotal challenge, particularly for lifeboats which could be called to address an emergency at any time. Beyond this, a medley of issues surfaces. Cables risk entangling with rudders or propellers, while geological formations could ensnare the ROV. Wind-induced instability on vessel decks poses further risks.[4]

ROV manoeuvrability is confined to speeds of 0.5 to 3 knots (0.23 to 1.54 m/s), limiting agility in strong tidal currents, similar to the AUVs discussed in section 2.1. Additionally, proficient ROV operation mandates comprehensive training, entailing both financial costs and labour investments. These challenges collectively underscore the consideration required to integrate Remotely Operated Vehicles into aquatic exploration.

## 2.3 SONAR

Sonar (Sound Navigating and Ranging) is a sophisticated technique utilising sound waves to communicate, explore, and map underwater environments by analysing echo patterns. The lifeboats of Nith Inshore Rescue Team are outfitted with a Raymarine RV100 transducer integrated into an Axiom MFD. This SONAR system allows precise structure identification and depth measurement. Despite its real-time seabed mapping capabilities, this technology lacks predictive functionality.

The dynamic nature of the estuaries considered, marked by rapid shifts, presents a significant challenge. The lifeboat volunteer operators note that the presence of steep-edged channels mean that depths can suddenly shift from depths of $>11$ feet to a mere 2 feet. This highlights the critical necessity for predictive systems that provide advanced insights before maritime operations commence, as included in 1.

Furthermore, a contemporary ecological awareness underscores concerns about the potential impact of underwater sound on marine life, encompassing auditory injuries and behavioural changes.[5] This ecological consideration introduces a nuanced dimension that could influence future SONAR selection, requiring users and developers to navigate the technological path forward in a conscientious manner.

## 2.4 Unmanned Aerial Vehicles

Unmanned Aerial Vehicles (UAVs) have become pivotal tools in oceanography and marine research. ATRALiTe's Edge LiDAR stands out as the world's first small-scale scanning system capable of topographic and bathymetric analysis, detecting underwater objects, gauging shallow water, and surveying vital underwater infrastructure from a compact UAV platform.[6] It operates effectively in the 0-5 metre depth range and achieves centimetre-level accuracy through Post Processing Kinematics (PPK) and Real Time Kinematics (RTK) techniques.

UAV deployment demands substantial training and supervision, potentially leading to labour-intensive efforts. Their lightweight nature renders them susceptible to wind, necessitating skilled piloting in adverse weather. Extreme conditions could ground the UAV for public safety. Additionally, the UAV is vulnerable to moisture, which may enter and damage its control system components. In summary, UAVs revolutionise marine studies, but their operation entails intricate considerations. Effective utilisation necessitates a balanced approach, incorporating training, weather vigilance, and safeguarding against environmental threats. These restrictions mean UAVs may not be a suitable form of mapping during extreme weather periods - precisely the times at which estuaries are expected to undergo the most significant changes.

## 2.5 Satellites

Satellites play a crucial role in delivering essential geographic and oceanographic data, and their reliability and precision make them a cornerstone of Earth observation studies. Access to satellite data varies, encompassing both open availability and commercially-restricted retrieval. These versatile instruments are capable of capturing diverse imagery, although cloud cover hampers the effectiveness of those equipped with visual imagers in regions prone to adverse weather conditions.

Addressing this limitation caused by persistent cloud cover, Synthetic Aperture Radars (SARs) present a promising avenue. Through the use of polarised radar signals, SAR data can be used to discern between sand and water, functioning adeptly even under nocturnal or cloudy conditions.[7] However, SAR imaging introduces its own intricacies. Patterns resulting from raindrop impact on the sea surface can enhance radar backscatter.[8] Moreover, the revisit frequency of satellites, spanning intervals from a few hours to several weeks, imposes constraints on the continuity of data acquisition.

In summation, satellites are pivotal assets for Earth observation, and the integration of SAR technology offers a remedy to cloud cover challenges. However, careful consideration of access costs and revisit schedules is required to facilitate seamless and comprehensive imagery acquisition.

### 2.6 Summary

In conclusion, while underwater and aerial vehicles exhibit utility within specific weather conditions, they fail to meet the user needs as outlined in Table 1. They are, therefore, unsuitable as stand-alone solutions but could be used as complementary tools to other imaging methods. Similarly, while SONAR technology is pivotal for rescue operations, it falls short in pre-establishing navigational routes. In contrast, satellite imagery emerges as the most viable option for tracking estuarine paths due to its autonomous nature and reliability, meeting all outlined user needs. Table 2 summarises the findings, comparing them to the User Needs set in Table 1.

Table 2: Fulfilled User Needs

| ID | AUV | ROV | SONAR | UAV | Satellite |
|---|---|---|---|---|---|
| U1 | ✓ | ✓ | ✓ | ✓ | ✓ |
| U2 | ✓ | ✓ | ✓ | ✓ | ✓ |
| U3 | ✓ | ✓ | ✓ | ✓ | ✓ |
| U4 | ✓ | ✓ | ✓ | ✓ | ✓ |
| U5 | ✓ | ✗ | ✗ | ✓ | ✓ |
| U6 | ✗ | ✗ | ✗ | ✗ | ✓ |
| U7 | ✗ | ✗ | ✗ | ✗ | ✓ |

## 3. REVIEW OF AVAILABLE SATELLITE IMAGERY

Having identified satellite remote sensing as an appropriate solution, system requirements for this can be generated as seen in Table 3. The images taken by these satellites must be collected at low tide and be of a suitable quality to allow the location of deep water channels to be clearly identified.[1] If images are unusable (due, for example, to the presence of cloud in visual imagery or high wind disturbances in SAR imagery), this increases the total number of images required to be collected per week by the satellite to increase the chance of having a reliable channel map. Furthermore, channels are expected to experience more frequent changes during times of heavy rain. Both of these factors combined lead to the distinction between system requirement S3 and S4 in Table 3. In this section, the different potential satellite alternatives will be discussed in light of the outlined requirements with the aim of identifying a suitable satellite solution.

Table 3: System Requirements

| ID | Description |
|---|---|
| S1 | Shall gather information about the path of the estuary. |
| S2 | Shall provide a safe route for lifeboats to navigate without running aground. |
| S3 | Shall sample the area in question at least 2-3 days a week during bad weather |
| S4 | Shall sample the area in question at least once a week during good weather |
| S5 | Shall sample a minimum area of 150 $km^2$. |
| S6 | Shall provide the route before the crew sets off. |
| S7 | Shall navigate and record data semi-autonomously or completely autonomously. |
| S8 | Should offer data at minimal to no cost. |

### 3.1 European Space Agency Copernicus Programme

The Copernicus programme is the European Union's Earth Observation programme which aims to achieve a global, continuous, autonomous and high quality Earth observation capacity. The domains covered by the seven missions in this programme include land, marine, atmosphere, climate, emergency and security. As previously highlighted, only satellites equipped with SAR imaging possess the capacity to effectively penetrate cloud cover—a capability of paramount importance, especially in regions susceptible to cloud formations, such as the Solway Firth. As such, noting the requirement of S3 in particular, only satellites equipped with SAR imaging will be considered in this review; within the Copernicus program Sentinel-1, -3, and -6 emerge as suitable candidates.

### 3.1.1 Sentinel-1

The Sentinel-1 mission features a tandem of polar-orbiting, sun-synchronous satellites, positioned with a 180°orbital phase disparity. These satellites engage in adaptable C-band imaging through four distinct modes, yielding resolutions as fine as 5m and swath widths spanning up to 400 km. Notably, the twin satellites are outfitted with a dual-polarisation SAR system, allowing for the transmission of signals in either horizontal (H) or vertical (V) polarisations, followed by reception in both H and V polarisations.[9] Sentinel-1 serves critical roles, from emergency response to sea ice, oil spills, and marine environment monitoring. A single satellite can map the global landmass every 12 days using Interferometric Wide swath mode, while the dual-satellite setup ensures a 6-day repeat cycle at the equator, with greater revisit rates at higher latitudes. European Space Agency (ESA) highlights daily high-accuracy, high-resolution coastal zone imaging. Notably, one satellite's malfunction last year has doubled the revisit time to 12 days.

### 3.1.2 Sentinel-3

Sentinel-3 comprises a pair of sun-synchronous satellites in near-polar orbit, each housing multi-spectral imaging instruments. The Scrambling Window Unit (SWU) within the Ocean and Land Colour Instrument (OLCI) camera system plays a pivotal role by shaping incoming light to optimize image quality. It acts as the camera's entrance pupil, mitigates stray light, reduces polarisation sensitivity, blocks UV radiance using a filter, and optimizes signal compatibility with the camera's sensor. This multifunctional component ensures accurate and high-quality image capture while enhancing the camera's performance across various environmental and illumination conditions.The satellites are in the same orbital plane but are 140°out of phase and have an orbital cycle of 27 days. The main objective is to measure ocean topography, sea and land surface temperature and sea and land surface colour with high accuracy to support ocean forecasting systems, environmental monitoring and climate monitoring.

### 3.1.3 Sentinel 6

Sentinel-6 consists of two identical satellites flown sequentially, offering real-time data on sea-surface heights, wave heights, and wind speed for oceanography and climate monitoring. Launched in 2020, the first satellite revisits every 10 days, while the second, set for 2025, aims to halve that interval. Poseidon-4 incorporates three key scientific instruments: the Poseidon-4 dual-frequency SAR altimeter for high-precision sea surface measurements, the AMR-C radiometer for accurate sea level monitoring, and the experimental HRMR enhancing Poseidon-4's SAR mode with millimetre-wave channels. Collaboration between ESA and NASA supports these advancements, while the mission also includes systems for precise orbit determination, global navigation satellite system radio occultation, and radiation environment monitoring.[10] Despite Sentinel-6A's 2020 launch and Sentinel 6B's upcoming deployment, providing years of operational life for future projects, limited data availability requires registration and subscription for access.

### 3.1.4 Third Party Mission Programme

ESA has established the Third Party Mission Programme, fostering collaborations with space organisations to enhance data accessibility from their respective missions. However, gaining access to satellite data or images mandates a registration or application procedure, potentially entailing labour-intensive efforts or uncertain outcomes. This initiative encompasses nearly 50 satellite missions, notably including TerraSAR-X and TanDEM-X, SAOCOM, COSMO SkyMed, PAZ, among others. These missions offer varying revisit times, ranging from 2 to 11 days, 6 days, 16 days, and even 24 hours. A comprehensive assessment, considering the specific orbital characteristics and swath width relevant to the designated region, can provide a more informed verdict on the practicality of harnessing these satellites.

## 3.2 Other Satellites

The aerospace industry is witnessing exponential growth, driven by the launch of satellites by various companies and organisations for independent research and data acquisition purposes. While this trend holds the potential for significant scientific advancements, a notable concern is the limited availability of the acquired imagery. Many entities naturally seek to generate profits from their findings, resulting in the imposition of membership fees. This section delves into an examination of commercial and non-commercial alternatives, with the objective of establishing which approach offers the most advantageous outcome.

### 3.2.1 RADARSAT-2

RADARSAT-2 is a collaborative satellite mission funded jointly by the Canadian Space Agency (CSA) and MacDonald Dettwiler Associates (MDA) for the Canadian government. Launched in 2007, it is a versatile platform supporting agriculture, hydrology, forestry, oceanography, and ice studies. The satellite employs SAR imagery in Single Polarisation (HH or VV) and Dual Polarisation (HH+HV or VV+VH) modes, enabling radar signal transmission and reception in horizontal (H) or vertical (V) polarisation. Dual-polarisation modes provide insights into vegetation, water bodies, and urban areas. Operating at 5.3 GHz in the C band, corresponding to a wavelength of 5.6 cm, RADARSAT-2 is accessible through a collaboration between ESA and MDA, offering unrestricted data access. Its revisit time of 24 days positions it as a valuable complementary system for various operational applications.[11]

### 3.2.2 ICEYE

Founded in 2014, ICEYE stands as a Finnish microsatellite enterprise. As of the onset of 2022, ICEYE boasts an array of 16 X-band (9.65 GHz) Synthetic Aperture Radar (SAR) satellites. These satellites also operate in both Single Polarisation (HH or VV) and Dual Polarisation (HH+HV or VV+VH) modes. The company's trajectory envisions further expansion across novel orbital planes, enabling sustained surveillance and delivering exceptionally high-resolution Earth surface imagery. This expansion aims to bolster reliability and significantly elevate revisit frequency. Presently, the revisit interval spans between 1 to 22 days. For scientific research endeavours, the European Space Agency (ESA) extends access to ICEYE's comprehensive data archive and tasking via the Third Party Mission programme.If the revisit rate proves favourable, the pursuit of this imagery through the proposal process could warrant consideration.

### 3.2.3 Capella Space

Capella Space, an American entity, is committed to the development of SAR-equipped satellites. Their core objective revolves around delivering the most frequent, timely, and superior-quality SAR images attainable. Notably, Capella is distinguished for its sophisticated analytics, adept at discerning critical elements and capturing nuanced changes—ranging from substantial to minute—that occur each day. With the successful deployment of a full constellation comprising 36 satellites in 2021, the remarkable outcome is a revisit time that dwindles to a mere 1-hour maximum. Capella's data distribution strategy entails a three-tiered structure: Tier 1 is accessible to the general public free of charge, while Tier 2 and Tier 3 offer specialised offerings that necessitate a formal application process.

## 3.3 Summary

Ideally, the use of a commercial satellite with an extended revisit time would provide the flexibility to acquire a sufficient number of images. However, the procedural requirements, which entail form completion, may prove time-consuming and potentially fruitless. An alternative strategy involves initiating the process with a satellite offering open access imagery. Through this approach, an evaluation of its revisit time and image quality can inform the decision to incorporate a second satellite. Should such a need arise, a commercial option could be introduced. This could yield cost reduction and mitigate the risk of application rejection, as a more precise understanding of optimal imaging parameters would be gained. For the ensuing analysis, the chosen satellite is Sentinel-1. Despite its potential for a lower revisit time, its imagery remains freely accessible, distinct from Sentinel 6, and offers a superior revisit interval in comparison to Sentinel 3. Table 4 summarises the findings using the system requirements set in Table 3, where the revisit characteristics of Sentinel-1 will be considered in further detail in section 4.

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[†] Further information needed regarding availability of imagery at low tide.

Table 4: Fulfilled System Requirements

| ID | Sentinel-1 | Sentinel-3 | Sentinel-6 | RADARSAT-2 | ICEYE | Capella Space |
|---|---|---|---|---|---|---|
| S1 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| S2 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| S3 | ? | ✗ | ✗ | ✗ | ? [†] | ? [†] |
| S4 | ? | ✗ | ✗ | ✗ | ? [†] | ? [†] |
| S5 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| S6 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| S7 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| S8 | ✓ | ✓ | ✗ | ✗ | ✗ | ✗ |

## 4. SENTINEL-1 DATA EVALUATION

Having identified Sentinel-1 as a suitable candidate mission, it is necessary to evaluate the frequency with which suitable images of the target region could be acquired. To do this, it is necessary to identify when Sentinel-1 passes over the Solway Firth and to couple this with the tide's state. Utilizing the Sentinel Hub EO Browser [‡], the specific day and time of Sentinel-1's traversal over the Solway Firth is determined. Alongside this, the high and low tide times from February to August 2022 are recorded for Carsethorn, (54.92,-3.58) a town approximately 9.2 km away from the Solway Firth region of interest. The corresponding tide height at that moment is manually sourced from an online UK weather forecast [§].

Ultimately, it becomes imperative to ascertain a reasonable estimate of the count of viable images per month. This endeavour aims to offer enhanced insights into the frequency and temporal distribution of Sentinel-1's image acquisition instances. In doing so, it facilitates the lifeboat rescue service in anticipating the availability of mapping data and determining instances necessitating supplementary mapping solutions for the estuary. To determine the monthly count of images attainable through Sentinel-1, a comparative analysis is essential. This involves assessing the tide's approximate height during overpass and juxtaposing it with the satellite image. Through this process, it is possible to ascertain moments when passageways become discernible, subsequently enabling identification of suitable tide height bounds within which usable images can be expected to be obtained. Figure 1 includes the images taken by Sentinel-1 during the month of May 2022.

Upon reviewing the images in Figure 1, it becomes evident that tide heights below 3.5m offer sufficient clarity to delineate the estuary's path. However, between tide heights of 3.5m and 4.5m, the route becomes less distinct. Further examination of various months revealed that, for instance, during April, a tide height of 4.2m remains usable for a clear image, depicted in Figure 2. This demonstrates that these tide height bounds should be considered as guidelines, as local variation in tight height and timing means that actual usability of data can vary. For the purposes of this assessment we hence assume that any image captured when there is a measured tide height at Carsethorn of 4.2m or lower could prove usable for route mapping to the sea, noting that the actual tide height in the Solway Firth may be higher or lower, given that the tidal measurements are taken approximately 10km from the region of interest.

Figure 3 portrays tide height in relation to the day of the month, affording a visual representation of the tidal fluctuations and their synchronicity with Sentinel-1's passes from February to August 2022. This showcases the count of viable and non-viable images (the dotted line representing the maximum tide height where images could be considered usable). Useful images per month range from five to eight, predominantly captured between the date ranges of 14th-18th and the 26th-31st. These clusters of images, averaging around 2 images each, exhibit an interval of approximately 10 days between consecutive clusters. Therefore, in accordance with the System Requirements detailed in Table 3, it is crucial to obtain at least one image (under optimal weather conditions) and a up to three images (during unfavorable weather conditions) to address the gaps in imagery during each monthly cycle. This realisation prompts the consideration of alternative systems to furnish imagery during such periods. The previously discussed methods outlined in section 2 present potential avenues for such alternatives.

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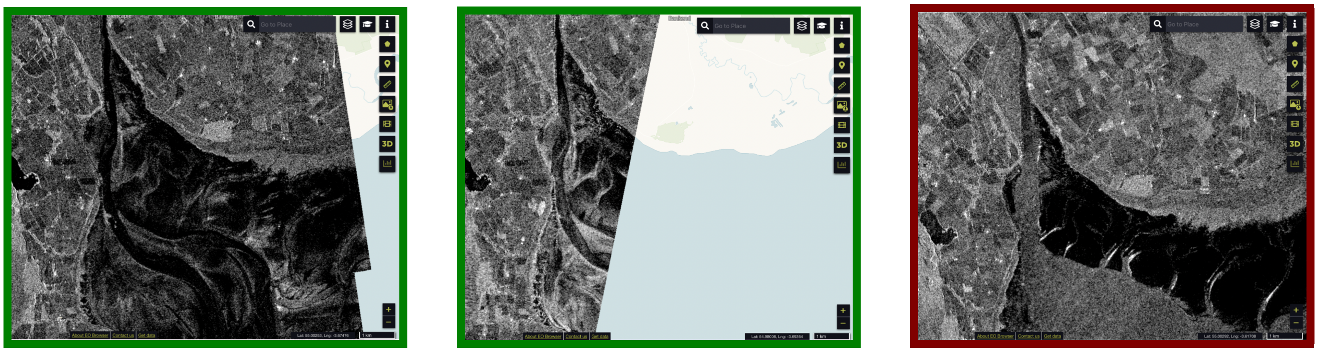
[‡] *https://apps.sentinel-hub.com/eo-browser/

[§] *https://www.willyweather.co.uk



(a) 03/05/2022 (2.2m)
(b) 05/05/2022 (2.6m)
(c) 10/05/2022 (4.5m)

(d) 12/05/2022 (3.5m)
(e) 15/05/2022 (0.1m)
(f) 17/05/2022 (0.5m)

(g) 22/05/2022 (7m)
(h) 27/05/2022 (0.4m)
(i) 29/05/2022 (0m)

Figure 1: Sentinel-1 Imagery of Solway Firth region of interest for the month of May 2022 with date and recorded tidal height listed. Green boundary indicates an image in which the channel is deemed to be viewable, while the red boundary indicates an image where the channel is not clearly visible.

Figure 2: Sentinel-1 image during 4th April 2022 (4.2m).

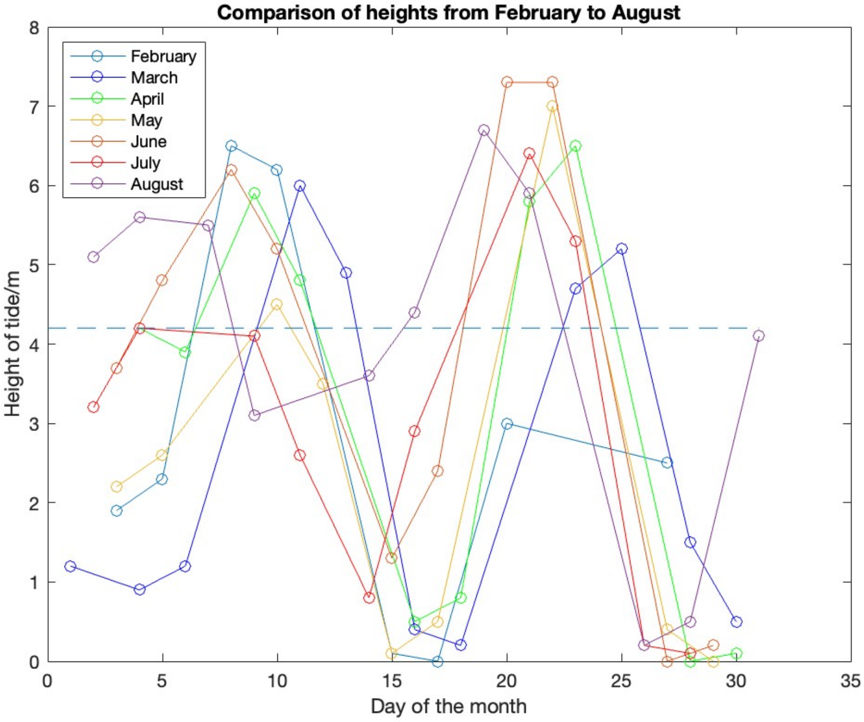


Figure 3: Comparison of tide height February to August 2022.

## 5. CONCLUSIONS

Satellite data is found to be the most suitable available technology to address the requirements of mapping dynamic estuaries to support lifeboat services in the Solway Firth. Sentinel-1 serves as a valuable tool for acquiring insights into the estuarine dynamics of the Solway Firth, and a range of other satellite systems have been identified that could provide additional or supplementary data. Nevertheless, the combination of Sentinel-1's revisit interval and the requisite sea level for valid imagery renders Sentinel-1 inadequate in meeting the criteria set by S3 in Table 3, falling short of the demand for 2-3 weekly images, especially in adverse weather scenarios. Consequently, the exploration of alternative approaches, as elaborated upon in Section 2, becomes imperative to bridge the gaps within the monthly data coverage with one to three supplemental surveys per month predicted to be needed.

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