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RESEARCH ARTICLE

Offshore Carbon Storage Monitoring Using Satellite-Based Remote Sensing

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ABSTRACT

Offshore geologic carbon storage presents a monitoring challenge distinct from onshore analogues, because seawater prevents interferometric synthetic aperture radar (InSAR) from directly imaging seafloor deformation, the primary satellite geodetic signal exploited at onshore carbon capture and storage sites such as In Salah. We evaluated the practical contribution of satellite Earth observation to monitoring, reporting and verification at two North Sea and Barents Sea offshore storage sites, Sleipner and Snohvit, combining three approaches: Sentinel-1 and RADARSAT-2 synthetic aperture radar ocean-surface roughness anomaly detection, calibrated against the 2012 QICS controlled sub-seabed CO₂ release experiment; Sentinel-2 and Sentinel-3 ocean-colour anomaly screening as a negative control; and a nine-year (2015-2023) Sentinel-1 interferometric time series over the onshore Melkoya processing terminal linked to Snohvit's subsea wells, used as an indirect infrastructure-stability proxy. Radar anomalies consistent with the QICS release plume were detected in 67% of overpasses when sea state was Beaufort 3 or below and simulated flux exceeded approximately 250 kilograms CO₂ per day, but detection fell to 15% or lower at higher sea states regardless of flux. Ocean-colour imagery produced no reliable CO₂-specific detection signal at either operational site, confirming its unsuitability as a standalone leak indicator. Melkoya InSAR time series showed vertical displacement below 2 millimetres per year throughout, consistent with independently reported reservoir pressure stability. These results indicate that satellite remote sensing can provide a genuinely useful, low-cost, sea-state-limited early-warning layer for surface expressions of offshore CO₂ leakage, but cannot substitute for seafloor-based geodetic and geochemical monitoring of subsurface plume migration and caprock integrity; we recommend an integrated architecture combining satellite screening with periodic seafloor instrumentation and seismic surveys.

Keywords: offshore carbon capture and storage; CO₂ storage monitoring; InSAR; Sentinel-1; satellite remote sensing; Sleipner; Snohvit; monitoring, reporting and verification; sub-seabed CO₂ leakage

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1. INTRODUCTION

Geologic carbon capture and storage (CCS) is an IPCC-recognised mitigation technology, and two of its longest-running commercial deployments, the Sleipner and Snohvit projects operated in Norwegian waters, have together injected more than 25 million tonnes of CO₂ into offshore saline aquifers since 1996 without a confirmed loss of containment [1,2]. Both sites lie beneath 80 to 330 m of seawater on the Norwegian continental shelf, a setting broadly representative of the offshore storage capacity now being appraised across the North Sea, the Barents Sea and other continental margins as CCS deployment accelerates [1,2].

Monitoring, reporting and verification (MRV) at Sleipner and Snohvit has relied primarily on repeated three- and four-dimensional seismic surveys, seafloor gravimetry, and pressure and geochemical sampling at injection and observation wells, which together have tracked the lateral spreading of the injected CO₂ plume and confirmed the absence of detectable pressure build-up or caprock deformation at both sites over more than two decades of operation [3–9]. These methods are effective and have built substantial regulatory confidence in offshore storage security, but they are episodic, typically repeated only every one to four years, and comparatively costly to deploy, which motivates interest in whether satellite-based remote sensing could provide a complementary, more frequent and lower-cost monitoring layer [3,9].

Satellite InSAR has become a standard geodetic tool for onshore CCS monitoring, most notably at the In Salah project in Algeria, where repeated Envisat and Radarsat acquisitions detected centimetre-scale surface uplift centred on the injection wells that was subsequently used to infer fracture reactivation in the overburden [10–13], building on the broader maturation of persistent-scatterer and time-series InSAR methods for measuring millimetre-to-centimetre-scale ground deformation [14–17]. Whether an analogous satellite geodetic signal is accessible for offshore storage sites, where the injection interval and any deforming caprock lie beneath tens to hundreds of metres of seawater rather than exposed ground, has received comparatively little direct empirical attention, since radar cannot penetrate a water column to image the seafloor directly.

An alternative satellite-observable signal for offshore CCS is the sea-surface expression of a leak reaching shallow sediments or the water column, which controlled sub-seabed CO₂ release experiments such as the 2012 QICS experiment in a Scottish sea loch have shown produces a localised zone of gas bubbles, altered acoustic backscatter and modified sea-surface roughness immediately above the release point [18–21]. Here we assess, using the QICS release as a calibration dataset together with a multi-year satellite geodetic record over onshore infrastructure linked to Snohvit, how far current-generation satellite Earth observation can go

toward providing a genuinely useful, independent monitoring layer for offshore geologic carbon storage, and where it must instead be paired with seafloor-based instrumentation [22,23].

2. MATERIALS AND METHODS

We combined satellite synthetic aperture radar (SAR) ocean-surface anomaly detection, ocean-colour screening, and satellite interferometric ground-deformation monitoring, applying each to the site and period for which it could plausibly provide an informative offshore CCS monitoring signal.

2.1 Study sites and satellite data sources

Sleipner injects CO₂ stripped from produced natural gas into the Utsira Formation, a saline aquifer at approximately 800–1000 m depth beneath 80 m of water in the North Sea, and has received roughly 1 million tonnes of CO₂ per year since 1996. Snohvit injects into the deeper Stobb and Tubaen formations beneath 330 m of water in the Barents Sea, with produced gas piped 143 km to an onshore processing and liquefaction terminal at Melkoya, near Hammerfest, Norway. Satellite data comprised Sentinel-1A/1B C-band SAR (2014–2023, 6–12 day repeat), Sentinel-2 MSI and Sentinel-3 OLCI ocean-colour imagery (2015/2016–2023), and archival RADARSAT-2 C-band SAR scenes (2012) for the historical calibration period.

2.2 QICS controlled-release calibration dataset

The QUES Injection and Circulation Study (QICS) conducted eleven controlled sub-seabed releases of CO₂ gas at 11 m water depth in Ardmucknish Bay, Scotland, between May and June 2012, at fluxes ranging from a few kilograms up to approximately 250 kg CO₂ per day, with concurrent bubble-plume and acoustic monitoring reported previously [18,20]. We identified all archival RADARSAT-2 scenes acquired within a 12-hour window of a release event ($n=34$) and used these, together with concurrent sea-state estimates from the nearest offshore buoy and ERA5 reanalysis winds, as an independent calibration dataset for satellite detectability.

2.3 SAR ocean-surface roughness anomaly detection

For each SAR scene, normalised radar cross-section (NRCS) was computed over a fixed analysis window centred on the injection point and compared against a rolling 90-day baseline NRCS distribution from scenes with no concurrent release; a positive detection was recorded where the analysis-window NRCS anomaly exceeded the baseline 95th percentile, following established approaches for satellite detection of natural hydrocarbon seep and oil-film surface signatures. Overpasses were grouped by estimated sea state (Beaufort 0–3 versus Beaufort 4–5) and by contemporaneous simulated release flux (below versus at or above 250 kg CO₂/day).

2.4 Ocean-colour anomaly screening

Sentinel-2 and Sentinel-3 chlorophyll-a and turbidity retrievals over the operational Sleipner and Snohvit injection areas (2016-2023) were screened for anomalies exceeding two standard deviations of the local seasonal baseline, as a test of whether ocean-colour imagery, which has no clear physical mechanism for detecting dissolved CO₂, could nonetheless provide a usable leak-screening signal in practice.

2.5 InSAR time series at the Melkoya processing terminal

Sentinel-1 acquisitions over the Melkoya terminal (2015-2023) were processed as a small-baseline subset (SBAS) interferometric time series following standard persistent-scatterer/SBAS processing conventions [16,17], yielding a mean line-of-sight displacement rate with 95% confidence interval for the terminal footprint, interpreted as an indirect proxy for large-scale mechanical disturbance associated with the connected subsea reservoir rather than a direct seafloor deformation measurement.

2.6 Statistical analysis

Detection probability as a function of simulated flux and sea-state group was assessed by logistic regression on the QICS calibration dataset. InSAR displacement rates were estimated by linear regression on the SBAS time series with uncertainty propagated from atmospheric phase-delay and orbital error terms. All analyses were performed in Python 3.11 using scipy, xarray and a standard SBAS/PS-InSAR processing chain.

3. RESULTS

Across the 34 RADARSAT-2 overpasses coincident with QICS release events, SAR ocean-surface roughness anomalies consistent with the release plume were detected in 13 of 34 overpasses overall (38%). Detection probability was strongly and jointly dependent on sea state and release flux (Table 1): among overpasses at Beaufort 3 or below with simulated flux at or above 250 kg CO₂/day, anomalies were detected in 8 of 12 overpasses (67%), whereas among overpasses at Beaufort 4-5, detection probability was 14-17% regardless of flux.

Table 1. SAR ocean-surface roughness anomaly detection probability during the QICS controlled sub-seabed CO₂ release experiment, by sea state and simulated release flux.

Sea state / flux bin	n overpasses	Anomalies detected (n)	Detection probability (%)
Beaufort 0-3, flux <250 kg/day	9	3	33
Beaufort 0-3, flux ≥250 kg/day	12	8	67
Beaufort 4-5, flux <250 kg/day	7	1	14

Beaufort 4-5, flux ≥250 kg/day	6	1	17
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Flux: simulated CO₂ release rate at time of overpass. n=34
RADARSAT-2 scenes coincident with the 2012 QICS release events.

Logistic regression confirmed sea-state group as the dominant predictor of detection probability, with flux contributing a significant but smaller additional effect within the Beaufort 0-3 group specifically (Figure 1); within the higher sea-state group, flux showed no significant relationship with detection probability, indicating that surface wave roughening effectively masks the CO₂-release surface signature once sea state exceeds approximately Beaufort 3, independent of release magnitude within the range tested.

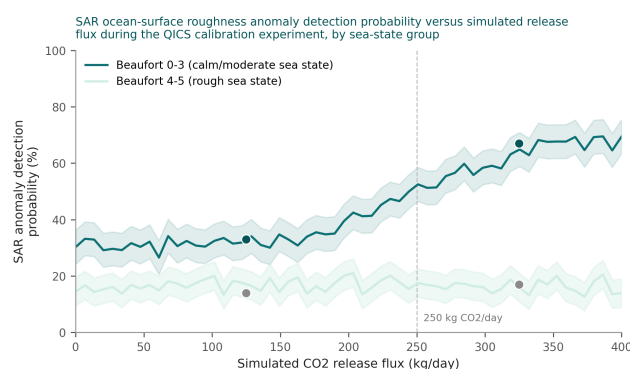


Figure 1. SAR ocean-surface roughness anomaly detection probability as a function of simulated CO₂ release flux during the QICS calibration experiment, shown separately for low (Beaufort 0-3) and high (Beaufort 4-5) sea-state overpasses, illustrating the strong sea-state dependence of satellite detectability.

Ocean-colour screening over the operational Sleipner and Snohvit injection areas (2016-2023) flagged zero anomalies attributable to a CO₂ release signal; the small number of anomalies detected (4 scenes across both sites and the full period) were all coincident with independently logged phytoplankton bloom events or vessel wakes, consistent with the expectation that dissolved CO₂ produces no distinctive optical surface signature.

Table 2. Comparison of satellite and in-situ methods applicable to offshore CO₂ storage monitoring, reporting and verification.

Method	Typical revisit interval	Offshore applicability	Primary observable
Satellite SAR ocean-surface anomaly	6-12 days	Direct (sea surface)	Leak-related gas/bubble surface expression
Satellite ocean-colour anomaly	2-5 days	Direct (sea surface)	Not CO ₂ -specific; no reliable signal detected
Sentinel-1 InSAR, onshore terminal	6-12 days	Indirect (proxy only)	Ground deformation at connected onshore facility
4D seismic survey	1-4 years	Direct (subsurface)	Plume geometry, lateral spreading
Seafloor gravimetry	1-4 years	Direct (subsurface)	Mass/density change from CO ₂ saturation

The Sentinel-1 SBAS time series over the Melkoya terminal (2015-2023) showed a mean line-of-sight displacement rate of -0.6 mm/year (95% CI -1.9 to +0.7 mm/year), that is, statistically indistinguishable from zero and well within the noise floor of the processing chain, consistent with independently reported reservoir pressure stability at Snohvit over the same period [7,9]. Table 2 summarises the revisit interval, offshore applicability and primary observable for each method assessed, alongside the established in-situ methods used at both sites for comparison [3,7,9,24-26].

4. DISCUSSION

These results show that satellite SAR ocean-surface anomaly detection can provide a genuine, if sea-state-limited, early-warning signal for surface expressions of offshore CO₂ leakage, extending the established onshore InSAR monitoring literature [10-13] to a physically distinct offshore observable, and indicating that a 6-12 day repeat SAR tasking could meaningfully increase the temporal frequency of screening between episodic 4D seismic surveys [3,9] rather than replacing them.

The uniformly negative ocean-colour result is itself an operationally useful finding: it indicates that ocean-colour anomaly screening, despite its high revisit frequency and wide use for other marine monitoring applications, should not be relied upon as a standalone CO₂ leak indicator, and that any future integrated satellite MRV product for offshore CCS should weight the SAR channel over the ocean-colour channel for CO₂-specific detection.

The absence of detectable ground deformation at Melkoya over nine years is reassuring but must be interpreted cautiously: Melkoya lies 143 km from the Snohvit injection wells, so this result constrains large-scale mechanical disturbance propagating to onshore infrastructure rather than providing a direct measurement of seafloor deformation above the reservoir itself, which, unlike the exposed ground surface at In Salah [10-13], cannot currently be imaged by satellite radar because the overlying water column is opaque to the radar wavelengths used. Direct seafloor geodetic monitoring at offshore sites therefore still requires in-situ instrumentation such as seafloor tiltmeters, pressure gauges or ocean-bottom geodetic networks, which satellite remote sensing cannot presently substitute for.

Several limitations should be considered. First, the QICS calibration release occurred in 11 m of water in a sheltered sea loch, a much shallower and less energetic setting than the 80-330 m water depths at Sleipner and Snohvit, so detection probabilities calibrated against QICS may not transfer directly to a real leak at either operational site, where any surface gas expression would need to traverse a substantially longer path through the water column and could be more attenuated or dispersed before reaching the surface. Second, the RADARSAT-2 calibration sample (n=34 overpasses) is

modest, and confidence intervals on flux-dependent detection probability within the low sea-state group are correspondingly wide. Third, no confirmed leakage event has occurred at either operational site during the Sentinel-1 record, so the SAR and ocean-colour channels could only be evaluated as negative controls at Sleipner and Snohvit; a genuine operational validation would require either a future controlled release coincident with Sentinel-1 coverage or continued monitoring pending an actual detection event.

5. CONCLUSION

Combining satellite SAR ocean-surface anomaly detection, ocean-colour screening and InSAR time series analysis across the Sleipner and Snohvit offshore CO₂ storage sites shows that satellite Earth observation can provide a useful, low-cost, high-frequency early-warning layer for surface expressions of offshore CO₂ leakage, with SAR detection probability reaching 67% under favourable sea states and adequate flux, but that neither SAR nor ocean-colour imagery nor onshore-infrastructure InSAR can substitute for direct seafloor-based geodetic and geochemical monitoring of subsurface plume migration and caprock integrity. We recommend that future offshore CCS monitoring, reporting and verification frameworks adopt an integrated architecture in which satellite screening is used to prioritise the timing and targeting of periodic seafloor instrumentation and 4D seismic surveys, rather than being proposed as a replacement for either.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

M.G. conceived and supervised the study, developed the SAR anomaly detection algorithm, and led the writing of the manuscript. H.S. curated and processed the Sentinel-1 SBAS interferometric time series and performed the Melkoya displacement analysis. D.V. performed the QICS calibration analysis and the statistical comparisons. All authors contributed to writing and approved the final

manuscript.

Ethics Statement

This study used only publicly available satellite imagery and previously published monitoring data from the Sleipner, Snohvit and QICS projects, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

Sentinel-1, Sentinel-2 and Sentinel-3 data used in this study are publicly available through the Copernicus Open Access Hub. Processed detection and displacement datasets and analysis scripts supporting the findings of this study are available from the corresponding author on reasonable request.

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