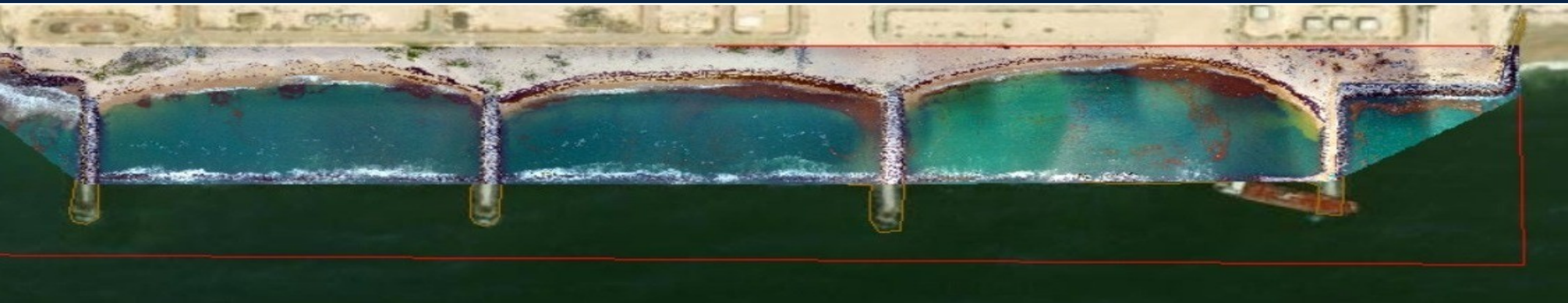
FEIC 2026 · Sub-theme ST6 Geomatics · Paper CMT-41

UAV-Referenced Calibration of Sentinel-2 Satellite-Derived Bathymetry on a Data-Scarce Open Coast

The Eti-Osa Shoreline, Lagos, Nigeria

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If a drone can map the land, can it also map the shallow sea?



The shallowest strip of our coast is the least surveyed



Land

GNSS, total station and drones map it routinely



The shallow strip

Surf, groynes, 0–5 m water: too wet for land survey, too shallow and rough for boats



Vessel zone

Echo-sounder vessels work safely once water is deep and calmer

Hydrographers call this unmapped band between land survey and vessel survey the "white ribbon". On the Lagos open coast it is also where waves break, sand moves fastest and coastal structures are built.

Key message The depths we most need for coastal decisions are the depths we measure least.

Why depth in this zone matters

Coastal protection

Groynes, revetments and beach nourishment are designed and maintained on nearshore depth and slope

Erosion and change

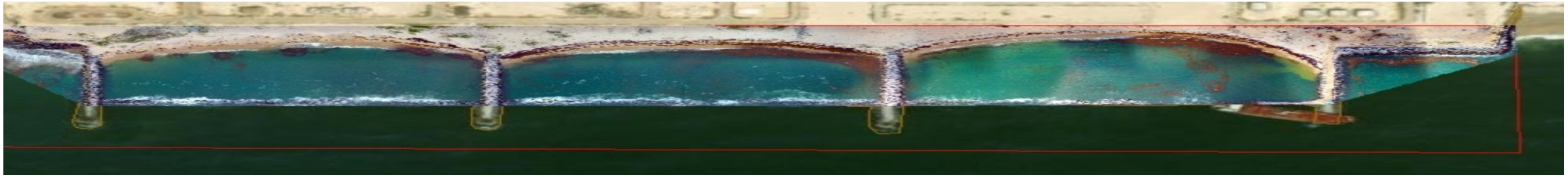
The Lagos coast is eroding; tracking the shallow seabed shows where sand is lost or gained

Safe access

Small craft, landing operations, rescue and pipeline or cable landfalls cross this zone

Planning and modelling

Wave, flood and sediment models, and marine spatial planning, all need nearshore depth



Key message Without nearshore depth, coastal engineering and management decisions are made partly blind.

Why it stays unsurveyed

Cost

Multibeam and single-beam systems, a survey vessel, crew and mobilisation are beyond the budget of most local firms, agencies and researchers

Risk

Breaking waves and groynes threaten vessels, transducers and crew; in very shallow water the multibeam swath shrinks, so coverage is slow and patchy

No reference

Free satellite imagery can estimate depth, but it must be calibrated with known depths, and those are exactly what is missing

Research question

Can depths from a low-cost drone survey stand in for missing charts and echo sounding as the reference that calibrates and validates free Sentinel-2 satellite bathymetry?

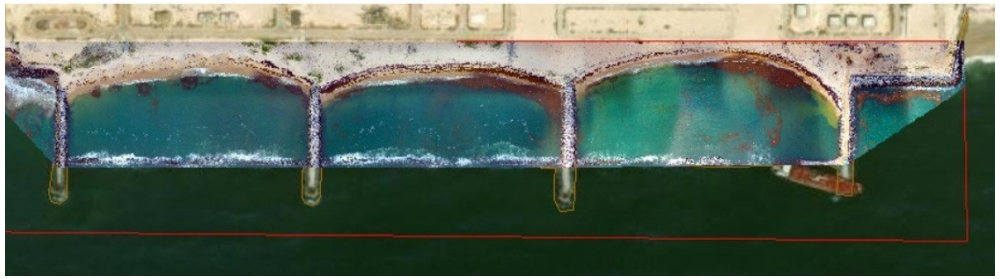
Aim and objectives

Develop and assess a satellite–UAV workflow in which drone depths calibrate and validate Sentinel-2 bathymetry for the Eti-Osa shoreline

1. Extract a quality-controlled UAV depth dataset and check it against field depths
2. Process and screen a Sentinel-2 scene for water, cloud, surf and glint
3. Aggregate UAV depths to satellite pixels; split by spatial blocks
4. Calibrate and compare empirical SDB models; select the primary model
5. Map depth, assess accuracy and fitness for use, test transfer

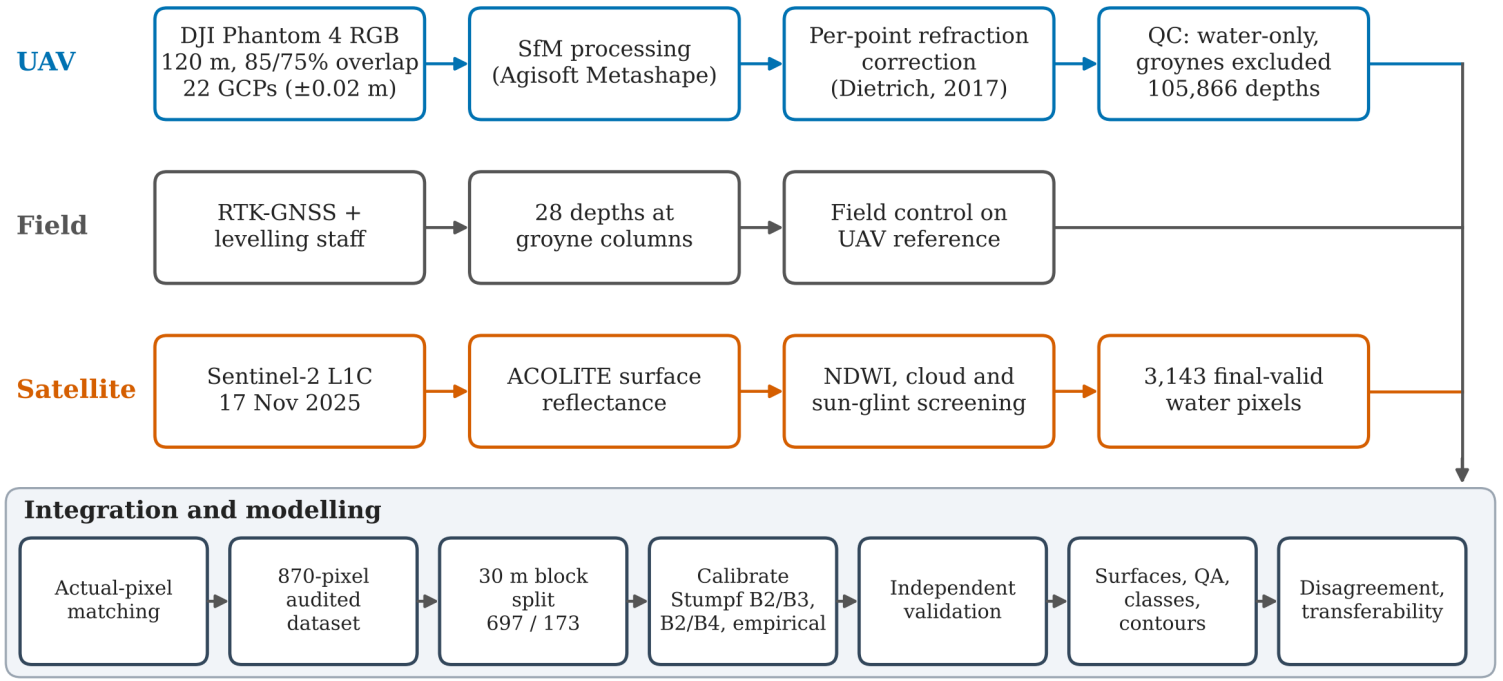
Study area and data





UAV survey	23 Apr 2026, 16:00–18:00 · DJI Phantom 4 (FC330) · 386 images at 120 m · 22 GCPs · 5 cm pixels · 57 % of the planned 49 ha flown
Field depths	28 RTK-GNSS + levelling-staff / bamboo-pole depths, 0.18–6.00 m, along groynes, same day 14:00–16:00
Sentinel-2A	17 Nov 2025, tile T31NEH · ACOLITE dark-spectrum fitting · 3,143 valid 10 m water pixels
Tide	TICON-3 harmonic predictions (Lagos gauge): all three surveys near low water

Workflow: three data streams joined at the satellite pixel



UAV: water surface from the survey; per-point refraction correction (Dietrich, n = 1.337) → 105,866 depths

Satellite: NDWI water mask; bright cloud and surf masked → 3,143 pixels

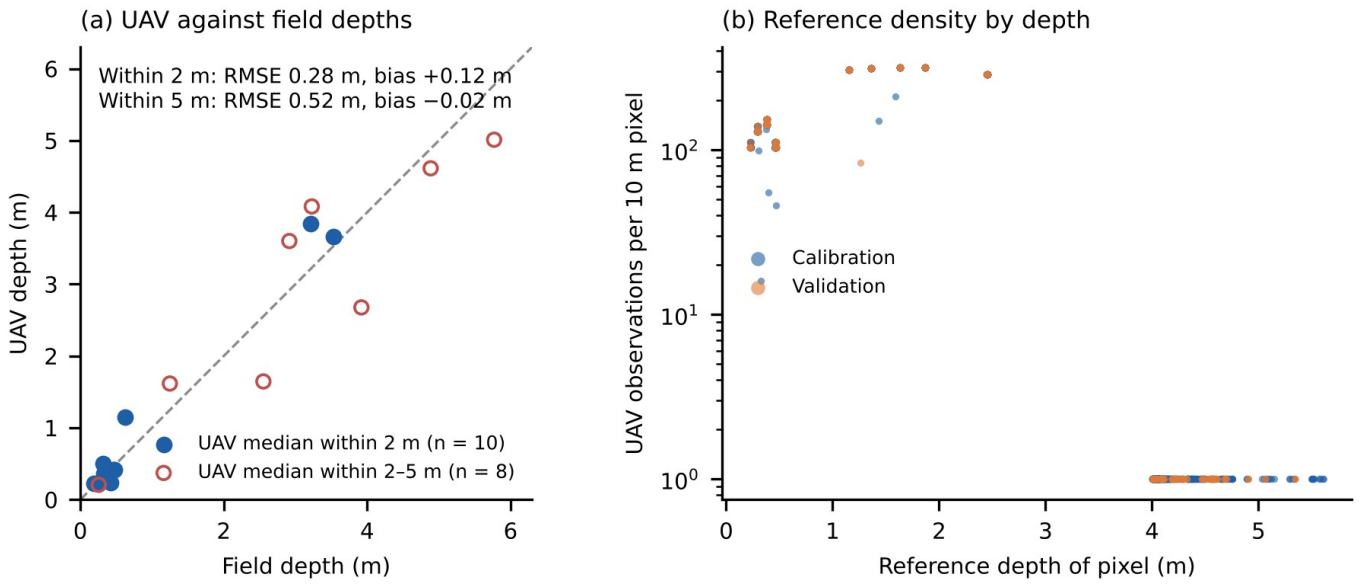
Matching: one depth per valid pixel → 870 pixels, 0.23–5.61 m

Split: 30 m blocks → 697 calibration / 173 validation

Models: Stumpf blue-green (primary), blue-red, empirical log; Lyzenga tested

Key message Every drone depth is refraction-corrected, then tied to exactly one satellite pixel.

First test: can the drone depths be trusted?



0.28 m

RMSE, 10 pairs within 2 m

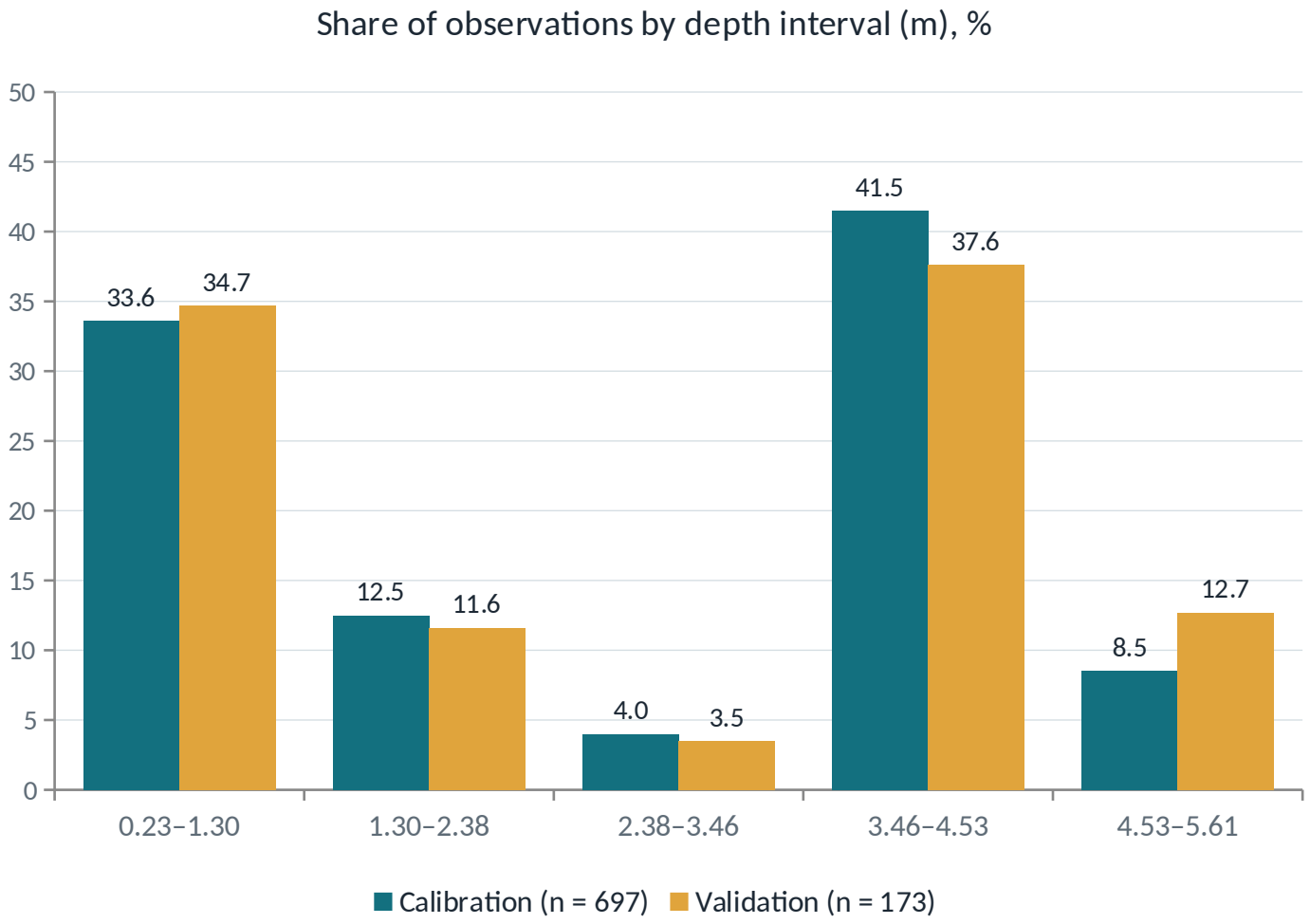
0.52 m

RMSE, 18 pairs within 5 m

- Close agreement in shallow water (r = 0.99)
- Fewer checks beyond about 3 m, where the drone sees less
- Shallow pixels rest on a median of 143 drone points; deep pixels on sparse points
- Tide differed by only 0.03 m between the two sessions

Key message The drone reference is reliable in shallow water; its reach, not its accuracy, is the limit.

A fair test: calibration and validation sets match



D = 0.08, p = 0.29

Kolmogorov–Smirnov: no significant difference between the sets

0.90–1.16 m

Validation RMSE over 200 random block splits (ours: 1.018 m)

- Blocks of 30–100 m tested; results stable
- Medians differ only because depths form two clusters; means differ by 0.008 m

Independent validation (n = 173)



0.677

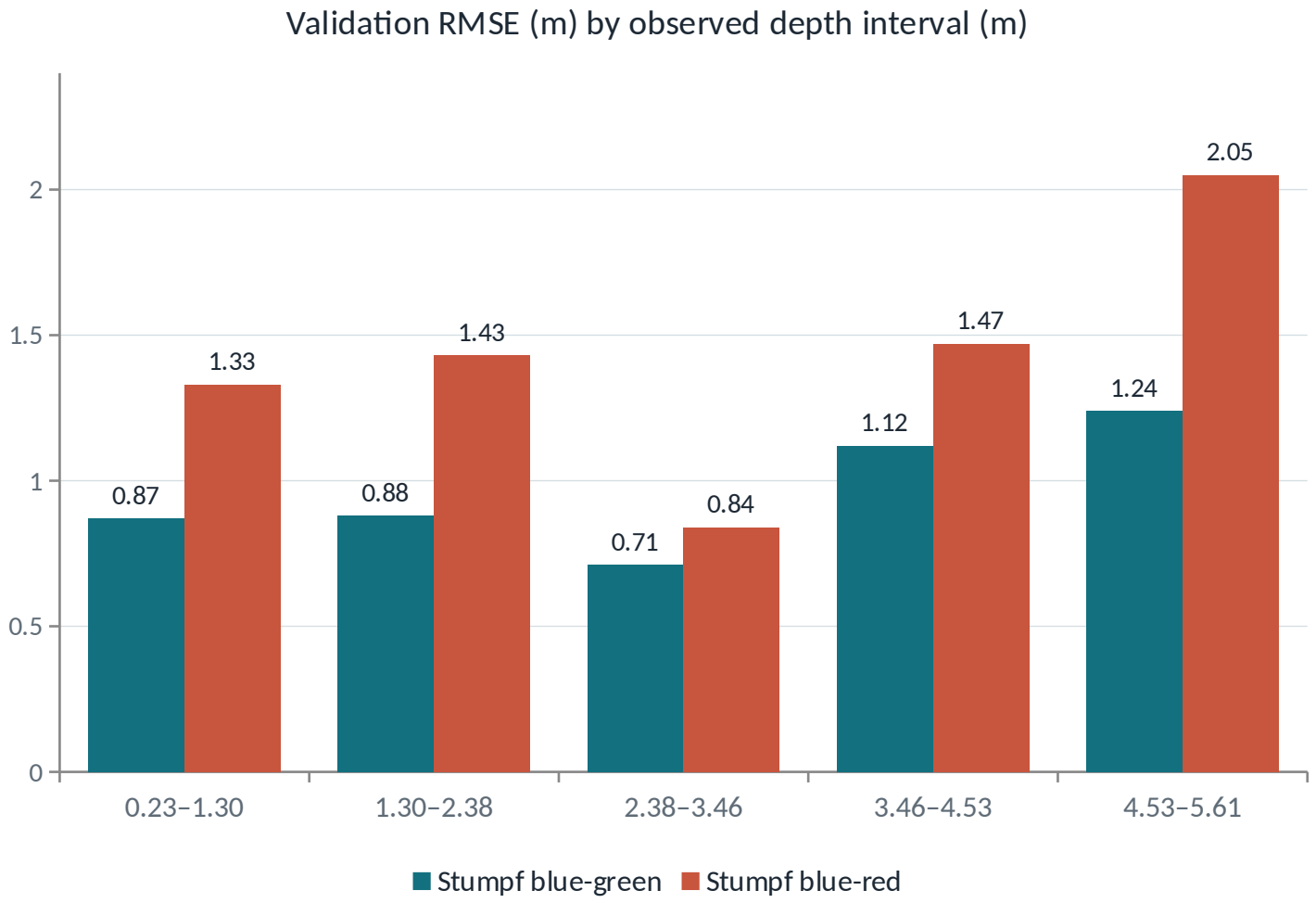
R^2 (95 % CI 0.56–0.75)

1.018 m

RMSE (95 % CI 0.90–1.13)

- Blue-green beats blue-red: RMSE 32 % lower
- Empirical model better by 0.03 m, consistently; kept as comparator
- Stumpf retained: fewer invalid depths (15 vs 33) and the established method
- Lyzenga not feasible: no optically deep water to anchor it
- Validation matches calibration (1.03 m): no overfitting

Blue-green wins at every depth: no band switching needed

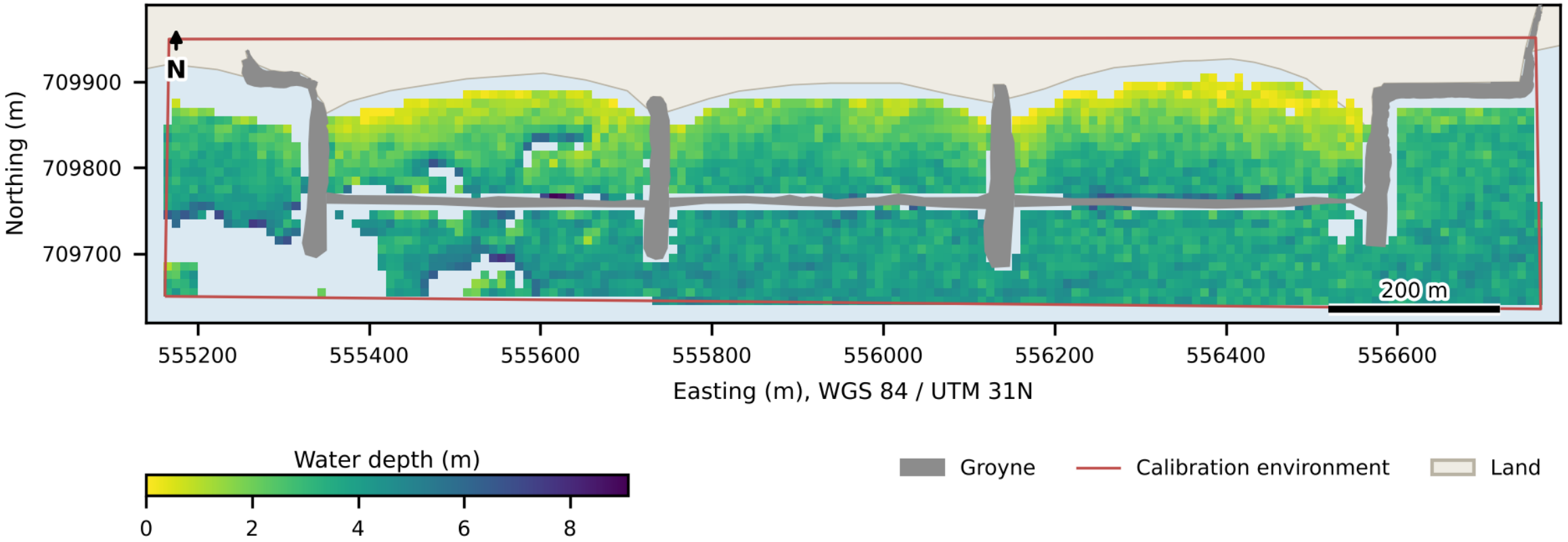


Bias by interval (blue-green)

0.23–1.30 m	**+0.63 m**
1.30–2.38 m	**+0.70 m**
2.38–3.46 m	**+0.39 m**
3.46–4.53 m	**−0.91 m**
4.53–5.61 m	**−0.66 m**

- Shallow depths over-estimated, deep ones under-estimated
- Small overall bias (−0.11 m) hides this; not corrected here
- Green light penetrates deeper than red, as expected

Final 10 m bathymetric surface (Stumpf blue-green)

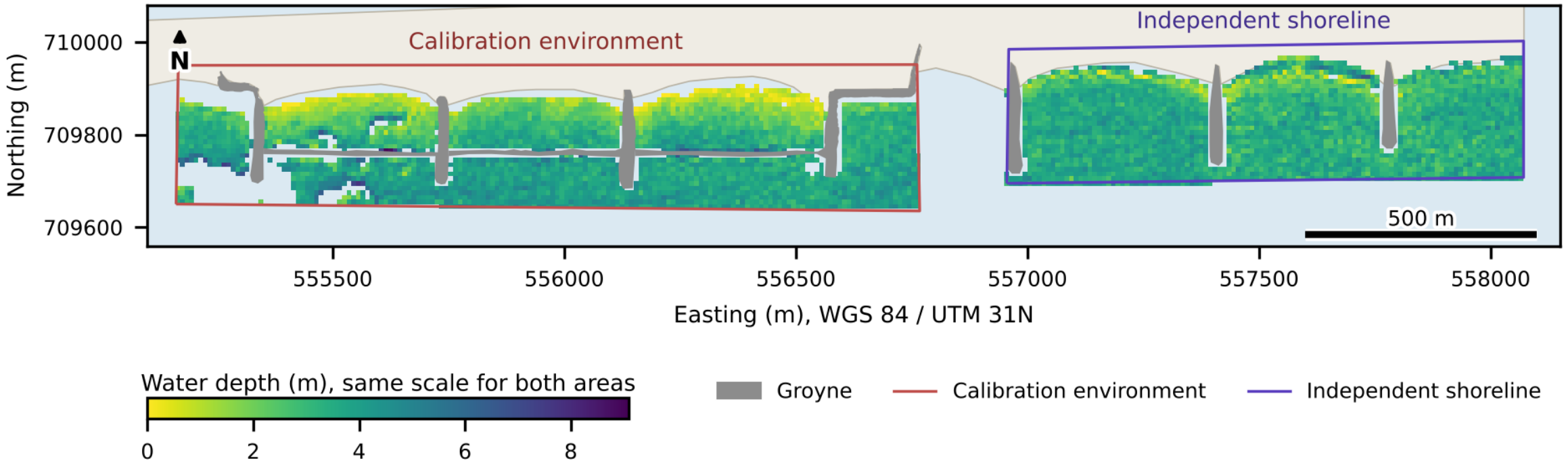


3,128 pixels
after masking 15 negative predictions

Mean 3.28 m
depth increases offshore in each groyne cell

> 5.61 m
extrapolated, not validated (26 pixels > 6 m)

Transfer to a nearby shoreline: plausible, not yet validated



- Same model, no re-tuning: 2,538 predictions, 99.57 % within the calibrated range; mean 3.35 m vs 3.26 m
- Weaker shoreward shoaling than in the calibration area; no reference depths there, so this is a plausibility check only

What the product is good for, and why tide is a minor factor

IHO CATZOC C

Approximate 95 % error ≈ 2.0 m: within zone C (2.0 m + 5 % of depth), outside A and B

≈ 2.8 m

Smallest change detectable between two such surfaces at 95 % confidence

0.88–0.98 m

Of the 1.018 m RMSE attributable to the satellite model after the UAV error

Survey	Time (WAT)	Water level vs MSL
Sentinel-2A, 17 Nov 2025	11:19	−0.25 m, rising
Field depths, 23 Apr 2026	14:00–16:00	−0.08 to −0.18 m, falling
UAV flight, 23 Apr 2026	16:00–18:00	−0.18 to −0.03 m, rising

- Suited to reconnaissance and survey planning: where it is shallow, deep or changing
- Not for navigation, dredging or engineering quantities
- Tide offsets are uniform or small (≤ 0.13 m) and absorbed by the model

Limitations and lessons from a first trial



This research began with a simple question: if drones map land so well, can they map water too? As a first trial, it did not get everything right, but it showed clearly how to do it better and more efficiently next time.

Time and scenes

Image five months before the drone survey on a moving sandy beach; one scene; validation within one corridor

Not measured

Water clarity, sea state, staff and pole uncertainty, and glint on the drone images were not recorded

Processing

No explicit sun-glint correction; depth-dependent bias not corrected; not reduced to chart datum

Coverage and reach

Drone lost in flight: 43 % of the planned area not flown; through-water reach about 5 m in clear water

Conclusions and next steps

Conclusions

- A low-cost drone survey, checked against field depths, can calibrate free Sentinel-2 bathymetry on a data-scarce open coast
- Stumpf blue-green: RMSE 1.02 m, R^2 0.68; blue-green at every depth, so no band switching
- A reconnaissance-grade map (≈ CATZOC C) for survey planning in the white ribbon, without putting a vessel in the surf

Next steps

Multi-scene compositing of many Sentinel-2 images to suppress turbidity and close the time gap

Same-window acquisition of drone and satellite data at a known tide

UAV bathymetric (green) LiDAR payload, where budget allows, to reach deeper and less clear water

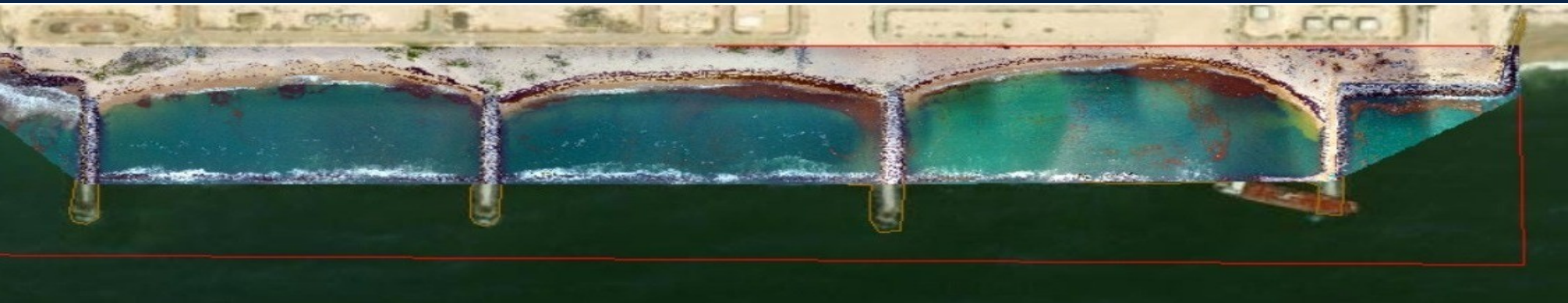
Denser field checks across the full depth range, plus glint correction and chart-datum reduction

Thank you

A drone can map the shallow sea, within limits we now understand.

Questions and comments are welcome

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Backup: anticipated questions (1 of 2)

Why not use an echo sounder for the reference?

The aim was a low-cost, low-risk route where vessels cannot work safely; field staff and pole depths checked the drone instead.

Why Stumpf, when the empirical model is slightly better?

The 0.03 m gain is negligible against the reference uncertainty; Stumpf gives fewer negative depths and is the established, transferable method. Both are reported.

Why could the Lyzenga model not be used?

It needs optically deep water. The deepest pixels were still brighter than average and their reflectance still tracked depth, so no deep-water value could be defended.

Is 1 m accuracy useful?

It matches the ~1 m usually reported for satellite bathymetry; ≈ CATZOC C, suited to reconnaissance and survey planning, not charting.

Backup: anticipated questions (2 of 2)

How was refraction corrected?

Point by point (Dietrich, 2017), using the cameras that saw each point and n = 1.337, with the water surface taken from the survey.

Why 30 m blocks, and is the result sensitive to the split?

Blocks stop neighbouring pixels sitting on both sides of the test. Over 200 random splits with 30–100 m blocks, RMSE stayed within 0.83–1.29 m (5th–95th percentile).

Why is the image five months older than the drone survey?

Cloud: only two near-cloud-free scenes existed and the closer one (Jan 2026) was cloudy over the corridor. Multi-scene compositing is the next step.

How deep can the drone see, and how was tide handled?

About 5 m in clear water; few points beyond 4 m. Tide from TICON-3: all surveys near low water; offsets ≤ 0.13 m and absorbed by the model.