# Recreational Sailing Fleets as a Coastal Observing System: A Citizen-Science Architecture and Metrological Methodology

Zoran Kovačević*, Amey Vasulkar†, and Hanno Hildmann†‡

* *Stichting Project SeaSense*, Amsterdam, The Netherlands, zoran@projectseasense.org

† Smart Sensor Systems lab, THUAS - The Hague University of Applied Sciences, Delft, The Netherlands, a.n.vasulkar@hhs.nl

‡ Collaborative Autonomous Systems (CAS) group, DSS, TNO, The Netherlands, hanno.hildmann@tno.nl

***Abstract*—Coastal seas are the best-observed part of the ocean and still under-sampled relative to their variability. Thousands of recreational and charter sailing vessels traverse these waters annually, measuring wind, depth and water temperature with on-board instruments. These measurements are never collected, recorded or aggregated. We present Project SeaSense: a tiered, low-cost architecture that turns such vessels into a crowd-sourced mobile coastal observing system together with a metrological methodology for processing this raw, uncalibrated data. SeaSense offers a complementary data collection effort to institutional monitoring, by harvesting a vessel's existing marine-bus instruments for data and augmenting that with onboard surface-pressure and motion measurements; an optional flow-through module adds water quality. We describe the concept of operations, analyse the dominant residual error per parameter and rank how much usable signal each channel should yield, and report on a 69-day endurance deployment. Surface pressure meets synoptic targets after a single scalar correction, harvested depth is usable in shallow water, and the two tiers correct each other; wet-chemistry channels met their sensitivity requirements but not their endurance. The contribution is the observing-system concept, its methodology, and a first per-parameter answer to how much signal opportunistic fleet data can yield.**

***Index Terms*—citizen science, coastal monitoring, vessels of opportunity, marine instrumentation, measurement uncertainty, sensor calibration, surface pressure, water quality**

## I. Introduction

The maritime environments on our planet are a primary buffer for various factors affecting our climate. Autonomous and opportunistic sensing platforms can complement existing dedicated, expensive infrastructure to measure this environment: individually or in swarms, unmanned aerial vehicles have been proposed to detect wildfires with minimal human supervision, underwater vehicles extend sensing below the surface [1]–[3], and GNSS buoys drifting through data-sparse seas can be seen as mobile tide gauges [4]–[6].

This paper applies the same idea (citizen science [7] with vessels of opportunity) to the recreational and charter sailing fleet, turning boats that are already instrumented and already moving into a coastal observing system. Doing so raises a metrological problem that, while routine on land, is rarely addressed at sea: instruments are uncalibrated and of unknown provenance, so their readings carry no traceable uncertainty. Closing that gap is at the core of the presented work.

### A. Motivation

Coastal seas concentrate human pressure, ecological value, and physical complexity. They are the most intensively observed part of the ocean, yet remain sparse relative to their small-scale variability and to the observation density taken for granted on land. Fixed stations are point measurements [8]; research-vessel time is scheduled and scarce; satellite retrievals degrade near shore [9]–[11]. For many coastal inquiries, there simply is not sufficient in-situ coverage at high enough revisit rates. Our approach aims to add mobile and repeatedly-sampling (opportunistic) sensing platforms [12], [13] to help.

### B. Approach

In this same zone sits an untapped instrument base. A modern sailing yacht already carries a masthead anemometer, an echo-sounder, a hull water-temperature sensor, and a network bus connecting them. Charter fleets re-sail the same waters weekly for a whole season. We capture this idle capacity in two tiers. The base tier is a single self-contained node that harvests the vessel's own instruments and contributes a few measurements of its own; nothing else is fitted to the boat. An optional second tier adds calibrated water-quality sensing and does require installed hardware: a pump, a sensor manifold, and a seawater circuit plumbed into the vessel. Both feed a pipeline built around meta-data provenance and per-vessel calibration. This frames the central open question the paper is built around: for each measured parameter (wind, depth, water temperature, and water-quality proxies), how much scientifically usable signal can be recovered from opportunistic fleet data once these metrological procedures are applied?

### C. Contributions of the paper

1) **Observing System Architecture:** A tiered hardware and data platform that harvests uncalibrated marine-bus sensors (Tier 1) and integrates modular flow-through water-quality sensing (Tier 2) aboard moving recreational sailing vessels.
2) **Metrological Quality Methodology:** A systematic framework combining instrument-identity tracking, repeat-route consistency, and opportunistic co-locations

against fixed stations to turn raw fleet data into tractable measurements with quantified uncertainty.

3) **Empirical Deployment and Tractability Ranking:** An in-water sea trial evaluating recoverable signal across all measured channels, establishing a per-parameter tractability ranking and identifying practical endurance limits for marine citizen-science platforms.

## II. Background

Project SeaSense joins a number of existing data collection efforts (Section II-A) for coastal environmental data that rely on opportunistic platforms (Section II-B) that aim at long-term maritime measurement (Section II-C).

### A. Maritime environmental data collection

State of the art in coastal in-situ observation: fixed buoys and stations, research cruises, ferry-of-opportunity flow-through systems (e.g. FerryBox [14]), integrated regional observatories combining in-situ platforms with remote sensing and modelling (e.g. COSYNA in the German Bight [15]), drifters and gliders, and satellite retrieval. Each trades coverage against cost, revisit rate, or near-shore fidelity. This work builds on decades of ships-of-opportunity and FerryBox programmes that have shown the value of scheduled vessels and flow-through systems for cost-effective ocean monitoring, and extends those concepts to recreational and charter fleets.

### B. Autonomous and opportunistic sensing platforms

Crowdsourced environmental observation is established: smartphone surface-pressure networks have demonstrably improved mesoscale analyses and forecasts [16], [17]; crowdsourced bathymetry is codified in IHO guidance [18]. The autonomous-systems literature frames such fleets as distributed, self-describing sensing platforms operating with minimal human intervention. This paper adopts that lens. The design is intended to be compatible with GOOS-style coastal observing systems built around Essential Ocean Variables [19], [20] and with emerging fleet-based networks such as the Fishing Vessel Ocean Observing Network (FVON) [21], which similarly leverage existing fleets as observing platforms.

### C. Challenges of long-term data collection at sea

There are three main challenge areas for marine, mobile, long-term data collection using vessels of opportunity:

- **Temporal:** i.e., endurance under power, biofouling, drift, intermittent connectivity, and seasonal coverage gaps.
- **Spatial:** data collection is extremely biased as it coincides with sailing locations, but this can result in high volumes of localized measurements as well [21], [22].
- **Data quality / calibration:** data is aggregated from consumer-grade instruments of unknown calibration state and siting, deployed on moving and heeling platforms.

## III. Project SeaSense

Project SeaSense is a non-profit initiative that aggregates maritime sensor data from charter operators, researchers and individual vessels through a common ingest interface and research platform. Its premise is that the cheapest marine sensor is the one already installed and already moving [14], [21]: we first use what the vessel measures, and add dedicated sensors only where the science needs them. Concretely, a vessel participates at one of two levels. A *Tier 1* install is a single self-contained node that harvests the vessel's existing marine-bus instruments and adds onboard surface-pressure and motion sensing. An optional *Tier 2* install additionally plumbs a calibrated, flow-through water-quality module into the vessel (hardware in Section IV).


Fig. 1. Two Project SeaSense trials (cf. Section V): [left] 2025 city trial using a paddleboard, in the city of Amsterdam, with [center] showing the course taken; [right] 2026 open water deployment from a boat around a governmental measuring station.

SeaSense is not a survey mission. The sensing nodes are vessels outside our control, whose owners choose Tier 1 or Tier 2 independently, may or may not share installation metadata, and sail when and where they please; the nodes log automatically. Normal sailing activity is leveraged as a repeat-sampling coastal sensor network. Skippers are nudged toward calibrating encounters through a gamified app, so the observing effort rides everyday sailing. The hard case is Tier 1: extracting usable signal from instruments that were never calibrated for this purpose [16]–[18], [23]. Four mechanisms and one structural asset, detailed below, address it. Tier 2's added water-quality sensors are calibrated by design and carry conventional, lab-traceable metrology. still ride the same provenance and encounter framework.

- **Instrument-identity harvesting.** NMEA 2000 product-information frames facilitate the unique identification of each transmitting device by manufacturer, model, firmware, and serial. Every sample is attributable to a specific physical instrument with a persistent identity, the prerequisite for per-instrument error modelling. Installation metadata that cannot be harvested (anemometer height, transducer offset) is captured once at install.
- **Repeat-route self-consistency.** Repeated passes over a sampling location separate the per-vessel systematic error from the environmental variability for any quantity whose truth is stable (such as depth) or stationary over the comparison window [18], [23], [24].

- **Validation by design.** The decisive objection to crowd-sourced calibration is the confound between sensor error and real environmental gradients. We attack it by raising the rate of useful co-locations: skippers are encouraged to pass near public reference stations (buoys, tide gauges, coastal stations, see Figure 1, right), turning rare chance encounters into more frequent, well-characterised ones with known spatial and temporal separation.
- **Per-vessel bias and drift profiling.** Encounters and repeat passes feed per-instrument error profiles (static bias, seasonal drift, per-channel quality grade), segmented by metadata completeness so rich fleet installs and minimal external feeds are analysed as distinct cohorts. This extends established blind/distributed sensor-network calibration [23] (recovering sensor gains and offsets from routine, uncontrolled measurements) to marine platforms.
- **Density as the enabling asset.** With many vessels on shared waters, cross-vessel agreement at crossings *maps* the local error field rather than extrapolating from one reference point. Density turns the hardest part of the inverse problem into interpolation, and density is exactly what charter economics provides.

Repeat-route self-consistency on depth was tested in a trial (cf. Section V) over 135 independent pass pairs, and co-location with reference stations on surface pressure.

## IV. System Architecture

The developed hardware follows a 2-tier model where Tier 1 is dedicated to harvesting data that is already created by a vessel while Tier 2 augments a vessels sensory capabilities.

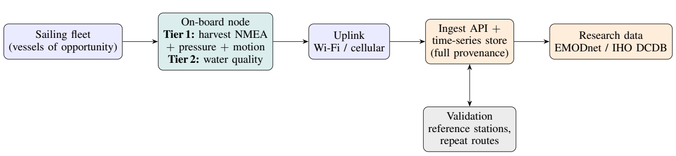


Fig. 2. The system architecture and data flow for Project SeaSense.

### A. Tier 1: self-contained harvest node

A compact logger (ESP32-S3) at the nav station, powered from the vessel's bus or 12/24 V system, battery-buffered, IP67, OTA-updatable, Wi-Fi and Cat-M1/NB-IoT uplink, dedicated GNSS (cf. Figure 3), with the uplinked over Wi-Fi to the vessel's satellite terminal. It listens galvanically-isolated and receive-only on NMEA 2000 (CAN) and NMEA 0183 (RS-422), harvesting wind, depth, water temperature, speed, heading, and position; three install paths cover vessels with N2K, 0183-only, or no bus. Onboard measurements are included: a barometric sensor (±1 hPa absolute, 0.4 Pa RMS noise, ±1 Pa short-term relative; one-point production calibration; Gore-Tex-vented enclosure) making the vessel a surface-pressure station, and a 9-DOF inertial unit for heel-corrected wind reconstruction and exploratory sea-state proxying [25]. BOM cost is in the low hundreds of euros; the cost of an additional parameter on an already-instrumented vessel is negligible.

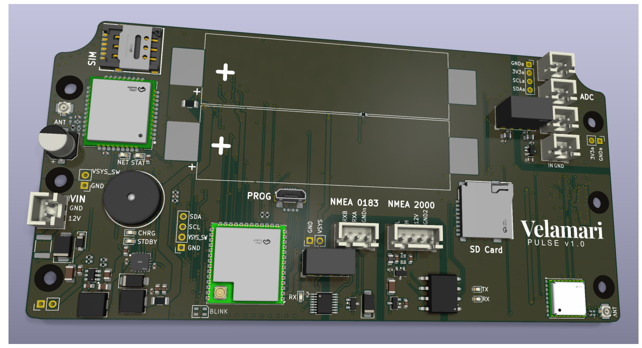


Fig. 3. The Tier 1 node hardware developed by Project SeaSense.

### B. Tier 2: calibrated water quality

An optional flow-through module [14], [26], [27] plumbed into the vessel: a pump draws seawater through a dark sensor manifold carrying pH, dissolved oxygen, electrical conductivity, and a PT-1000 temperature probe, on a flush-then-read cycle to limit biofouling and stale-water readings. Unlike Tier 1, this tier installs hardware (pump, manifold, seawater circuit) on the boat. Conductivity and PT-1000 are the robust anchors; pH and DO take temperature/salinity compensation from the co-located channels. Its BOM cost is on the order of €1000, an order of magnitude above Tier 1 but still far below laboratory-grade water-quality instrumentation.

### C. Pipeline and provenance

Observations are buffered locally and uploaded (Wi-Fi / cellular) to a partner-agnostic ingest API, where a time-series store maintains continuous aggregates. The data model is sparse (sensors report independently, so a vessel with only an echo sounder contributes as readily as a full install) and every sample carries its provenance: instrument identity, vessel, and installation metadata. Store-and-forward is what makes the platform viable where connectivity is intermittent: on the final North Sea leg two gaps that began under way, backfilled in a single burst on regaining the link, one of them delivering 13 observations at unbroken 15.5-minute cadence.

Our telemetry shows why provenance cannot be an afterthought: on Tier 2 it is the calibration chain. The PT-1000 is the only traceably calibrated probe in the manifold; the node reads it first and hands its value to the pH, dissolved-oxygen and conductivity probes as their temperature compensation, so those three channels are only as good as the temperature they are given. Two defects follow. Water temperature reaches the platform from three different instruments — the PT-1000, the compensation channel carried by the chemistry probes, and an unidentified harvested NMEA source — differing by 0.4 °C in the median and distinguishable only by instrument identity, so which temperature compensated which reading is recoverable only from provenance. And although every wet probe was calibrated against reference fluids on the bench before departure, that act was never captured: one telemetry record in a thousand carries a calibration date. The calibration was performed, the record was not kept, and traceability is the record. Ingest currently applies no range gates; the automated quality control this implies is discussed in Section VII. Context travelling with each datapoint is also what later makes selection effects measurable rather than hidden.

## V. Trial deployments

We report 3 escalating field trials of increasing duration, platform, and water variety (see Figures 1 and 4).

1) **Human-powered board** (May 2025, ≈1 month). Water-temperature and conductivity sensors towed by a paddleboard (see Figure 1, left/center): a first proof of the water-quality channels and the logging chain.
2) **Small craft** (≈2 months, Amsterdam canals and the Markermeer). The same sensing across contrasting inland waters, exercising endurance and a range of conductivity and temperature regimes (see Figure 1).
3) **Cruising yacht** (June–August 2026, endurance deployment). Tier 1 and Tier 2 were installed aboard a Contest 63CS in June 2026. The vessel departed Medemblik on 29 June and reached Knokke on 16 August (Figure 4). This is the endurance and integration deployment and the first sea-going run; its results are reported in Section VI.

The first 2 are development milestones only, Trial 3 is the first season-long, zero-access deployment on a cruising vessel.

The Tier 1 node draws a nominal 2.5 W (0.10 A at 24 V); the Tier 2 pump adds 2 A for 20 s per 15-minute cycle, about 1.1 Ah/day. Total consumption is 3.6 Ah/day at 24 V (≈86 Wh), an amount easily absorbed by the host vessel's house bank. On a dedicated 12 V 100 Ah battery the same load runs 7–11 days depending on chemistry, and a ∼30 Wp panel makes Tier 1 energy-neutral in summer. Trial 3 was powered from the yacht's instrument panel rather than off-grid; with the consequences (panel-off in harbour) already mentioned.

Sampling is on a common cycle. The Tier 2 wet sequence runs every 15.5 m and is gated off when the vessel is stationary or the pump is inhibited by the owner. Tier 1 pressure, inertial and NMEA channels are sampled continuously and reported once per cycle as instantaneous values; GNSS is read every cycle. While this is adequate for synoptic pressure, where hourly reporting is the WMO norm, for depth, and for thermohaline fronts (the Den Oever front was resolved at nine samples in 124 min, it is not adequate for sea state, which needs continuous inertial windows to yield significant wave height or period.

## VI. Data collection and first results

We use the frozen set of 1,080 observations to 10 August at a median cadence of 15.5 minutes from the Trial 3 cruising yacht data for the validation statistics. Channels differ sharply in recoverable signal (Table I, rightmost column); each is reported against the best available independent reference.

**Availability:** 3 distinct issues affected data collection: (1) when the crew switches the instrument panel off in harbour (in this case gaps begin below 1 kn and are never backfilled — the four weeks alongside before departure yielded 84 observations); (2) equipment fault, but this does not have to result in total data loss (wind feed data stopped on day 6 at sea due to a cable fault on the vessel's own bus, while every other channel continued at over 99%); (3) degraded offshore communication (gaps can be backfilled in a burst later).


Fig. 4. Trial 3 (Medemblik, 29 June, to Knokke, 16 August 2026; n = 1,206 under-way observations), coloured by harvested-channel availability: all channels live (dark, n = 334) and Tier 1 without wind from the vessel's wind-cable fault of 5 July (light). Markers: departure (○), conductivity probe failure at Den Oever (×), wind-cable fault (+), and the offshore communications gap of 12 August that began at 8.9 kn and was backfilled on regaining the link (◇). The 84 observations from the moored period (2–28 June) are not shown; statistics in the text use the 1,080 observations to 10 August. Route: IJsselmeer → Den Oever → German Bight → Elbe → Kiel Canal → Fehmarn Belt → open Baltic → Stockholm archipelago, returning to Knokke.

**Surface pressure:** Pressures were compared against the nearest of 28 KNMI, DWD and SMHI synoptic stations, all reduced to mean sea level. The node reads 1.01 hPa high across all 1,080 observations ($\sigma$ = 0.60 hPa), and 0.96 hPa high against stations within 25 km ($\sigma$ = 0.49 hPa, n = 415; Figure 5a). The offset does not drift: on the stationary subset it holds to $+0.00 \pm 0.08$ hPa per 30 days, with scatter of 0.35 hPa (Figure 5b). Because the node sits at sea level, the offset is instrumental, and it falls inside the sensor's $\pm1$ hPa specification. One co-location with a reference station removes it, cutting RMSE from 1.08 to 0.49 hPa — within WMO and GOOS targets. What remains, up to $\pm1$ hPa in the daily mean under way, is the vessel sampling a synoptic gradient 30 km from its station: representativeness, not the instrument.

**Depth:** Against the survey-derived EMODnet digital terrain model (669 matchups) the harvested sounder shows no scale error (slope 0.984) and a residual of $+0.37 \pm 1.24$ m in water shallower than 5 m, growing to $-1.6 \pm 7.1$ m beyond 50 m, where the reference itself is interpolated and leisure sounders are at the edge of their range. Repeat-route self-consistency

TABLE I

PER-PARAMETER MEASUREMENT, DOMINANT RESIDUAL ERROR, VALIDATION STRATEGY, AND EXPECTED TRACTABILITY REFERENCES MOTIVATE THE MEASUREMENT OR ITS IMPLEMENTATION; THE LAST COLUMN GIVES THE MEASURED OUTCOME OF THE TRIAL 3 DEPLOYMENT (SECTION VI).

| Parameter | What is measured | Dominant residual error | Validation strategy | Tractability | Trial 3 result |
|---|---|---|---|---|---|
| Barometry [16], [28] | Surface air pressure at interior mount | Per-vessel mount location (uncontrolled, time-stable); cabin pressurisation; airflow at speed | Vs. public synoptic obs; speed-filtered | Highest | +1.0 hPa, $\sigma$ 0.49 ($\leq$25 km), no drift over 69 d; one co-location $\rightarrow$ 0.49 hPa RMSE |
| Bathymetry [24] | Water column depth below transducer | Transducer offset; tide datum | Repeat passes over static ground; tide correction | High | slope 0.984 vs EMODnet; +0.37 $\pm$ 1.24 m below 5 m; repeat-pass 0.45 m (0-10 m) |
| Water temperature [14] | Bulk near-surface ($\approx$0.3–0.9 m), *not* SST | Inter-vessel mount-depth under stratification | Repeat-route offsets; encounter deltas | Medium-high | +0.09 °C, RMSE 1.68 °C vs CMEMS |
| Conductivity (T2) [14] | EC in flow cell | Fouling (dark flush-then-read manifold) | Transits across contrasting salinity regimes | Medium-high | correct in fresh water; resolved the Den Oever front in 124 min; failed the same day, first day at sea |
| Wind [29], [30] | Apparent wind at masthead | Rig/superstructure flow distortion; heel; under-sail aerodynamics | Motoring segments as clean-flow anchor; cross-vessel agreement | Low-Medium | r 0.86 vs ERA5, $-11°$ vane bias; feed lost day 6 at sea (cable) |
| pH, DO (T2) [26], [27] | Flow-cell chemistry | Fouling, aging; DO most stale-water-sensitive | Co-located T/EC compensation; reference encounters | Low | pH responsive and reproducible (Elbe plume on two crossings), unvalidated; DO under-reads $\approx \frac{1}{3}$, not reportable |
| 9-DOF motion | Vessel response to sea state | Hull transfer function (RAO) unknown per vessel | n/a | Exploratory | healthy 69 d; no sea-state product transmitted |

over 135 independent pass pairs (both under way, at least 24 h apart, within 500 m) gives a median disagreement of 0.45 m in 0–10 m of water, the band for crowdsourced bathymetry [18].

Tier 2's temperature and conductivity supply the sound-speed correction the sounder lacks (1487 m/s measured against 1500 m/s assumed), moving the slope to 0.992 and the deep-water bias from $-2.0$ to $-1.4$ m, complementing Tier 1.

**Water temperature [14]:** The Tier 2 probe reads +0.09 °C against satellite sea-surface temperature (CMEMS) on marine legs (757 matchups, RMSE 1.68 °C), and the two onboard probes agree to 0.36 $\pm$ 0.52 °C; the scatter is intake depth and reference resolution, not the sensor.

**Conductivity [14] and pH [26], [27]:** Conductivity read fresh water correctly through the 4 weeks alongside (851 $\mu$S/cm in the IJsselmeer) and resolved the Den Oever estuarine front in full (1.5 to 46.3 mS/cm in 124 m) before failing 3.5 hours later, on the first day at sea. pH tracked the same mixing (r = 0.99) and resolved the Elbe plume on two crossings 42 days apart (along-track profile correlation 0.84), corroborated by temperature on both; it has no external reference in these waters and remains unvalidated. Dissolved oxygen under-read by about a third and is not reported. The binding constraint on Tier 2 chemistry was endurance, not sensitivity.

**Wind [12], [29], [30]:** Harvested masthead wind agrees with ERA5 at r = 0.86 and with 139 coastal stations at r = 0.74, with a $-11°$ direction bias against both, a vane-alignment constant of the kind per-vessel profiling removes. Direction scatter falls from 59° to 8° as the wind builds. The reference comparison inverts between the two Tier 1 channels: for pressure the stations beat the reanalysis, for wind the reanalysis beats the stations. In open water a fleet of barometers adds information and a fleet of anemometers does not; whether that holds in archipelagos and gap-wind regimes remains to be seen.

**Counting:** Recorded are tracks where consecutive observations share weather, water mass and instrument state, capturing independent passes and crossings rather than observations.

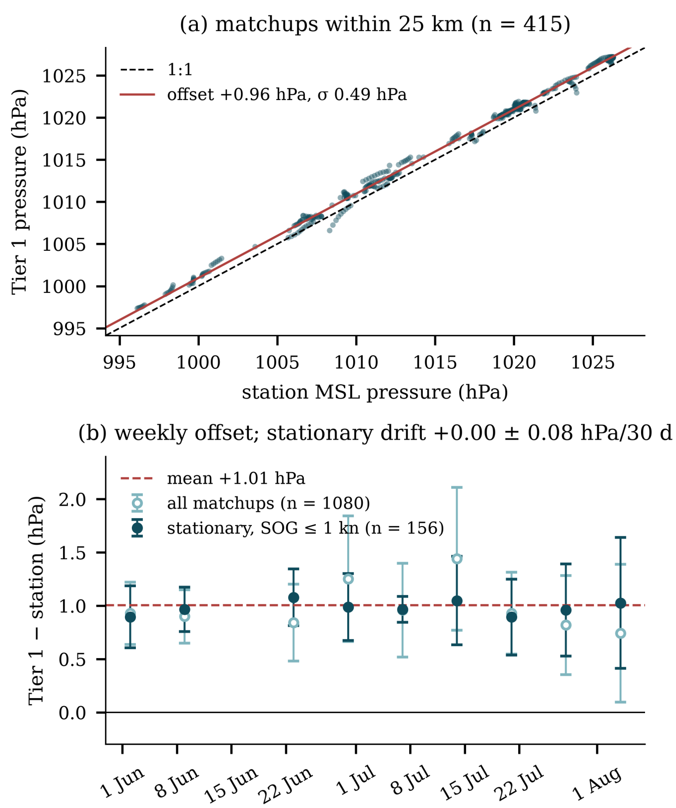


Fig. 5. Tier 1 barometer against the nearest synoptic station (28 KNMI / DWD / SMHI stations, pressure reduced to mean sea level), Trial 3 frozen set, 2 June – 10 August 2026 (n = 1,080). (a) Matchups with a station within 25 km: offset $\pm$0.96 hPa, $\sigma$ 0.49 hPa. (b) Weekly mean offset $\pm$ 1$\sigma$ for all matchups (open) and for the stationary subset, SOG $\leq$ 1 kn (filled); the stationary offset drifts +0.00 $\pm$ 0.08 hPa per 30 days. One co-location correction brings the residual to 0.49 hPa RMSE.

## VII. CRITICAL REFLECTION, LIMITATIONS, AND CONCLUSION

Recreational sailing fleets offer dense, repeated spatial coverage in coastal zones where fixed monitoring networks remain sparse. We presented an architecture that harvests standard marine-bus telemetry alongside modular flow-through wet chemistry, accompanied by a metrological methodology to ensure measurement tractability. Our in-water trials demonstrate that surface pressure reaches synoptic standards after a single offset correction, harvested depth aligns closely with reference bathymetry, and flow-through chemistry captures sharp estuarine gradients before encountering endurance limits.

However, several metrological challenges remain. Wind measurements under sail carry substantial hydrodynamic and aerodynamic distortions that limit their utility in open water, and sea-state estimation requires vessel-specific transfer functions that are not yet established [25]. Furthermore, recreational fleet sampling is inherently opportunistic and non-uniform, reflecting seasonal and fair-weather routes.

The next phase of Project SeaSense involves expanding to a multi-vessel fleet trial to evaluate cross-vessel consistency and automated ingest filtering. A further derived product is surface current: combining GNSS velocity over ground with vessel velocity through water may yield along-track current estimates, subject to heading, leeway, and instrument-alignment corrections. Such in-situ estimates could complement optical wake-based methods, whose coverage is constrained by satellite revisit, vessel speed, and cloud cover [31]. By streaming quality-controlled soundings and surface observations into platforms like EMODnet, recreational vessels can provide continuous, low-cost coastal monitoring at scale.

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