Author comment (AC) — response to referee comments

Manuscript egusphere-2026-994: *"Improving geolocation and footprint characterisation of microwave radiometer observations using coastal crossings"* by Frank Fell, Ralf Bennartz, and Bruno Picard

First, we would like to express our gratitude to both referees for their careful and constructive assessment of the manuscript, and for the positive overall evaluation. The detailed comments have helped us sharpen the presentation of the method, clarify its underlying assumptions, and make its limitations explicit. We address all raised points below and indicate the corresponding changes to the manuscript.

Two subjects raised independently by both referees — the impact of footprint ellipticity (R1-MA1 / R2-MI2) and the influence of environmental heterogeneity (R1-MA2 / R2-MA3) — are answered jointly, with cross-references at the respective comments.

Referee 1

Comments to Authors:

This paper presents a data-driven in-orbit approach to improve microwave radiometer geolocation and footprint characterization using coastal crossings. By maximizing the correlation between observed brightness temperatures and modelled effective land fractions (ELF), the authors estimate along-track geolocation error (ELON), across-track error (ECRO), and full width at half power (FWHP). The study uses a large ensemble of global coastal crossings and a two-round iterative random-effects meta-analysis framework to reduce parameter interdependence and quantify uncertainties. The results demonstrate systematic geolocation biases and mission-dependent footprint characteristics, with implications for improving coastal wet tropospheric correction in satellite altimetry. Overall, I find this to be a technically strong and valuable study, and I would recommend the manuscript for publication after satisfactory responses to the comments provided below.

Major Comments:

R1-MA1: Although the paper later evaluates footprint geometry and aspect ratios, the actual TB–ELF correlation optimization is still performed using a circular/symmetric Gaussian footprint model. This may be biased in cases where the true antenna response is elliptical or asymmetric. The manuscript would benefit from either incorporating elliptical footprint parameters directly into the optimization framework or providing quantitative evidence that the circular approximation does not significantly affect ELON, ECRO, and FWHP retrievals.

[==> See also comment R2-MI2 of referee 2.]

As both referees raise the circular-footprint assumption, we respond to R1-MA1 and R2-MI2 jointly.

To quantify the effect of an elliptical antenna beam, we repeated the TB–ELF correlation optimisation using elliptical Gaussian footprints in the calculation of the ELF, based on a re-processing of 100 randomly selected half-orbits (Envisat, Cycle 007, 23.8 GHz) to obtain ELON, ECRO, and FWHP for aspect ratios a/b = [0.8, 0.9, 1.0, 1.1, 1.2]. The elliptical footprint is defined with its a-axis aligned with the flight direction (along-track) and its b-axis across-track, so that a/b < 1 corresponds to a footprint wider across-track and a/b > 1 to one elongated along-track. It is rotated into the geographic frame at each position; the implementation was verified to preserve the footprint centroid under scaling and rotation, so the model introduces no spurious geolocation shift.

We find that the sensitivity of the aggregated corrections ELON and ECRO to ellipticity is small. Over realistic aspect ratios of the instruments considered (a/b ≈ 0.94–1.06, Table 5), the aggregated ELON and ECRO change by less than ~0.05 km — at or below the 50 m precision with which these parameters are determined (Sect. 4.2), and therefore not resolvable by the method itself. Even at the exaggerated ±20 % ellipticity tested as a robustness check (a/b = 0.8, 1.2), the aggregated ELON and ECRO change by at most ~0.2 km.

FWHP, i.e. the circular-equivalent footprint width, shows a larger, monotonic response up to a few kilometres, which is expected: because the retrieval is performed by optimisation against real TB observations, FWHP adjusts so that the modelled footprint's projection onto the coastline matches that of the true instrument footprint. An imposed ellipticity that departs from the true beam shape is therefore compensated by a corresponding shift in FWHP.

The results provide quantitative evidence that the circular approximation does not significantly affect the aggregated ELON and ECRO corrections over the realistic range of MWR antenna ellipticities, and that the FWHP response is a controlled, physically expected compensation rather than an artefact. The analysis reported above has already been carried out; the corresponding text and table will be added to Sect. 6.3.

R1-MA2: The methodology assumes that TB variations across coastal crossings are primarily controlled by land–water emissivity contrast. However, atmospheric humidity gradients, surface temperature variability, precipitation, and complex coastal morphology may also influence TB–ELF correlation maxima. A more detailed sensitivity analysis quantifying the impact of environmental heterogeneity on retrieval accuracy would strengthen confidence in the robustness of the approach.

[==> See also comment R2-MA3 of referee 2.]

As both referees raise the influence of environmental heterogeneity, we respond to R1-MA2 and R2-MA3 jointly.

We distinguish two cases:

1.) Random, overpass-uncorrelated perturbations — variable cloud cover, tidal state, small-scale coastal morphology — do not bias the retrieval but increase the scatter of the individual crossings. They tend to cancel in the aggregation over many observations, as reflected by the large spread of individual retrievals alongside a stable aggregated value. Gross outliers can distort both the *aggregated value and its uncertainty; they are therefore removed by rejecting retrievals deviating by more than 2.5 σ from the corresponding cycle mean (Sect. 5.3.3).*

2.) Systematic, locally persistent perturbations — such as land-surface temperature contrasts within the radiometer footprint (for example, the strong thermal contrast near mountainous coasts such as the Andes, noted by referee 2), or cloud and precipitation — are the bigger concern. A perturbation will bias the retrieved ELON/ECRO/FWHP if it moves the position of the maximum correlation away from the true coastline; however, any such displacement necessarily degrades the correlation between the observed TB and the land fraction simulated from the (unperturbed) land–sea mask. This provides a means to identify observations suitable for the retrieval procedure: coastal crossings leading to a correlation coefficient r > r_thresh are retained for further analysis.

We adopt r_thresh = 0.999 as an empirical, pragmatic value, applied uniformly across all instruments, channels, and parameters, estimated from the Envisat crossings of the ten analysed cycles. Envisat is used because its superior radiometric sensitivity compared to its predecessors reduces the instrumental noise level such that perturbation-caused correlation reductions become more apparent. This is illustrated in Fig. RESP-1 below, showing a marked increase of the absolute deviation of individual retrievals from the mean as the correlation coefficient decreases; the chosen threshold lies within this transition region, where deviations begin to rise, rather than in the well-correlated bulk.

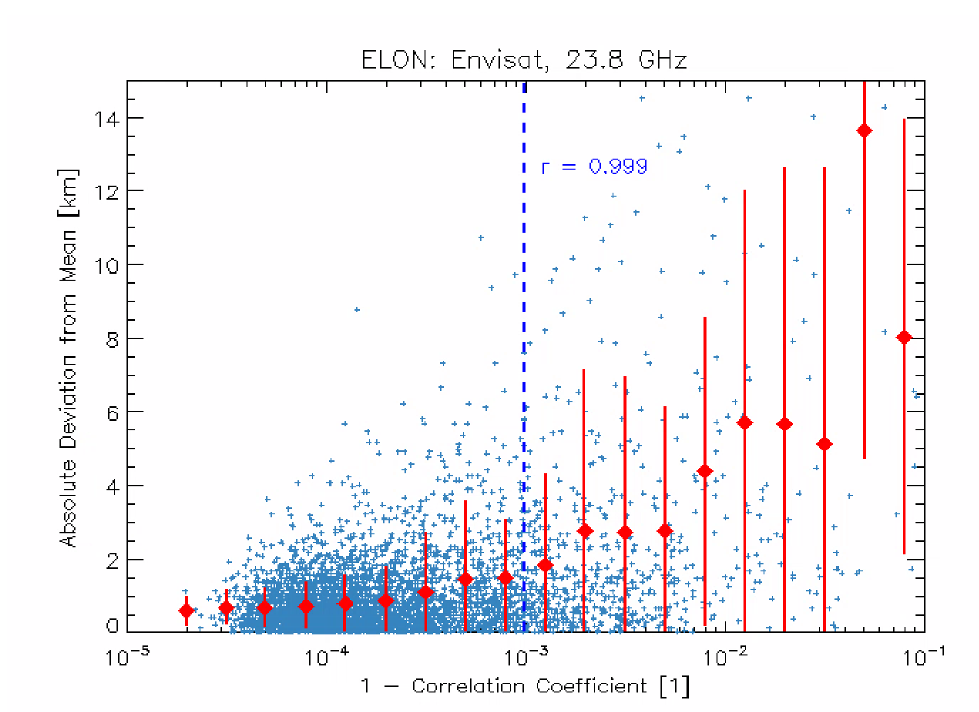

Figure RESP-1: Absolute deviation of individual ELON retrievals from the overall mean (over all ~3500 retrievals) as a function of the correlation coefficient (plotted as 1 – r on a logarithmic axis), for all Envisat coastal crossings across the ten cycles analysed (23.8 GHz). Blue points are individual crossings; red symbols with bars show the binned mean and standard deviation. The dashed line marks the applied threshold r_thresh = 0.999. The deviation increases as the correlation decreases, with the threshold placed at the onset of this rise. ECRO and FWHP show the same behaviour.

An instrument- and channel-specific optimisation of the threshold is deemed beyond the scope of the present study but could be considered for more recent sensors (e.g. Sentinel-3, Sentinel-6).

The threshold justification and Fig. RESP-1 given above will be incorporated into the revised Sect. 5.3.3.

R1-MA3: The Mann-Kendall test is applied with N = 10 repeat cycles per mission and a relaxed significance threshold of $\alpha = 0.10$, explicitly chosen to compensate for low statistical power (lines 538–541). With N = 10, the MK test has very limited power to detect subtle monotonic trends: for a two-tailed test at $\alpha = 0.10$, the minimum detectable effect size (in terms of Kendall's τ) is large, meaning that moderate but physically meaningful drifts could easily go undetected. The paper correctly identifies one significant trend (ERS-2, 36.5 GHz ELON, p = 0.03) and attributes it to gyroscope failures, which provides important physical validation. However, for ERS-2's 23.8 GHz channel, split-period ELON estimates are provided (Table 4) showing a shift from 1.46 ± 0.13 km to 1.71 ± 0.13 km — a ~0.25 km change that, while not meeting the $\alpha = 0.10$ threshold (p = 0.37), is physically plausible given the same gyroscope event. The authors should report explicit power calculations or confidence intervals for the trend estimates and consider whether bootstrapped uncertainty bounds on the MK statistic would be more appropriate given the small sample size and potential serial correlation across adjacent orbital cycles.

We agree that the MK test has limited power at N = 10. We address the raised points as follows.

***Serial correlation**. As shown in Table A1, the ten cycles per mission are distributed across the full mission lifetime, with separations of months to years between successive analysed cycles. The cycle means are therefore not temporally adjacent, with the single exception of a few closely spaced ERS-1 cycles, so the MK independence assumption is justified. We will add a sentence in the manuscript stating this.*

***Bootstrapped uncertainty bounds.** With N = 10, only strong monotonic trends (corresponding to a large Kendall's τ) can be resolved at any conventional significance level; this is an inherent property of the sample size and is precisely why we adopted the relaxed $\alpha = 0.10$. Given the very small sample size, resampling is unlikely to provide meaningful additional information beyond the per-cycle uncertainties already reported in Table 4 (±0.13 km); we therefore prefer to report the split-period estimates directly.*

***The ERS-2 23.8 GHz ELON case.** We agree the ~0.25 km shift (1.46 to 1.71 km, Table 4) observed for ERS-2 23.8 GHz ELON is physically consistent with the same gyroscope event, even though it does not reach the significance threshold $\alpha = 0.10$ (p = 0.37). This is why we include split-period estimates for the 23.8 GHz channel (lines 558–560): to allow for a consistent correction strategy across both channels regardless of formal significance. We will revise the text accordingly: the shift is qualitatively consistent with the gyroscope event, but the sample size is too small to resolve it statistically.*

***Follow-on investigations:** While N = 10 reflected what we considered a reasonable balance of temporal coverage and processing effort for these heritage missions, we suggest processing more repeat cycles (e.g., N ≥ 20) to increase statistical power for future applications of the method (e.g., to Sentinel-3 and Sentinel-6). We will note this in the Conclusions.*

We further consider that the gyroscope failure merits closer attention than can be provided by the present mission-wide sampling (ten cycles across the full lifetime) can provide. A dedicated study using denser sampling around the failure period (February 2000 – January 2001) would be better suited to resolve the associated drift in both channels; this is a natural follow-up but lies beyond the scope of the present characterisation.

Minor Comments:

R1_MI1: The manuscript would benefit from a brief discussion of computational cost and runtime, particularly given the large number of coastal crossings and iterative optimization procedure.

The processing was carried out with scientific research software written in IDL 7.1.1, an interpreted language, running in a virtualised Linux environment (openSUSE Leap 15.6, 20 GB RAM) on a basic desktop workstation (Intel Core i5-10400). The code is moderately optimised, guided by profiling. For example, the land/sea mask and distance-to-coast grids are held on a RAM disk to speed up access, and file search is based on precomputed file lists.

The retrieval is performed in two iterations: a first round using a nominal footprint identical for all observations, and a second round in which the per-instrument and per-channel values derived at the end of the first round are applied. The aggregated geophysical parameters ELON, ECRO, and FWHP are thus derived from two rounds over 250 randomly selected passes per cycle across 10 cycles for each of the three instruments (2 × 7,500 passes in total). Considering the processing time for an individual pass of typically 6–7 s, this corresponds to about 25–29 hours of elapsed time on a single core; a single round of 250 passes for one cycle takes roughly half an hour.

The current implementation runs sequentially; as the processing of each crossing is fully independent, it would parallelise and scale near-linearly with the number of available cores.

The above discussion of computational cost and runtime will be added as a new Appendix D.

Referee 2

General Comments:

This manuscript presents a novel methodology for measuring and correcting MWR geolocation pointing errors using correlation between on-orbit brightness temperature measurements and modelled effective land fraction. The approach employs an iterative optimization technique that successfully reduces ambiguity in error components while simultaneously measuring antenna beam diameter, thereby enabling improved sea level determination in coastal regions. The study demonstrates robust methodology supported by a statistically significant number of measurements across each of three missions: ERS-1, ERS-2, and Envisat. Successful detection of a known gyroscope failure on ERS-2 provides validation of the method's sensitivity and results are consistent with previous literature. The method is clearly presented and directly applicable to future missions, including Sentinel-3 and Sentinel-6.

This work represents a significant and well-executed contribution to the field but there are a few things I suggest addressing in the specific comments below.

Major Comments:

R2-MA1: Figures 2-5: These figures are difficult to interpret because symbol definitions are presented in Panel 1, which lacks visual representations of the various symbols and line types. While Panel 1 provides useful explanatory text, each figure should include its own self-contained legend for improved clarity and accessibility.

> *We agree that the symbol definitions should be visually accessible rather than described in words alone. However, adding a self-contained legend to each of Figs. 2–5 would introduce substantial redundancy, as these figures share a single common set of conventions (Panel 1). We will therefore add a column to Panel 1 showing the actual graphical symbols alongside their textual descriptions. This provides the requested visual reference in one central place, while keeping the individual figures uncluttered.*

R2-MA2: The flow diagram effectively illustrates the overall process but omits the outlier rejection and correction threshold described in Section 5.3.3. Including these critical components would provide a more complete representation of the iterative method.

> *We agree. We will amend Fig. 10 to include the post-retrieval quality filters described in Sect. 5.3.3 — outlier rejection (±2.5 σ) and the correlation threshold (r < 0.999) — as a distinct step between the per-crossing retrieval (step 5) and the meta-analysis (step 6). This will make the diagram consistent with the revised description in Sect. 5.3.3 (see our replies to **R1-MA2** and **R2-MA3**).*

R2-MA3: Section 4.1: The filtering process would benefit from additional criteria to remove spurious measurements. Specifically, filters should detect and exclude: (1) cloud contamination, (2) known tidal flats, and (3) coastlines adjacent to mountainous terrain. For example, coastlines near the Andes in South America routinely show cold temperatures on one side and warm temperatures on the other, creating artificial contrast that mimics a false coastline displaced from the actual coast. These features may not be adequately captured by existing filters.

*Referee 1 raised similar concerns; this comment has therefore been answered together with the corresponding comment from referee 1. See our answer to **R1-MA2** above.*

Minor Comments

R2-MI1: Beam Smearing: The paper would benefit from explicitly addressing beam smearing effects. Signal integration during platform motion causes the effective antenna beam to smear in the along-track direction. Accounting for this effect would improve correlation accuracy and provide better initial conditions for the optimization algorithm. The measured beamwidths correspond to the effective smeared beam rather than the static beam pattern.

We agree that beam smearing should be addressed explicitly. As the referee notes, the retrieved beamwidths correspond to the effective, motion-smeared beam rather than the static antenna pattern. This is consistent by construction in our approach: the parameters are retrieved by correlating the already smeared brightness temperature observations with the modelled ELF, so the retrieved ELON, ECRO, and FWHP inherently describe the smeared beam. Since the resulting corrections are subsequently applied to the same beam-smeared observations, there is no mismatch between the correction terms and the observations. We will add a paragraph in Sect. 3.1 stating this.

R2-MI2: Antenna Beam Shape Assumption: The measurement process assumes a circular antenna beam, and Section 6.3 presents results supporting this assumption. However, this analysis may contain bias due to the circular assumption built into the modeling approach. While likely a small effect, using an elliptical antenna beam model when calculating effective land fraction would strengthen the results and eliminate the need to defend/prove the circular assumption is valid.

*Referee 1 also raised the question of the potential impact of footprint ellipticity on parameter retrieval; this comment has therefore been answered together with the corresponding comment from referee 1. See our answer to **R1-MA1** above.*

R2-MI3: The paper would benefit from showing corrected geolocation error statistics in a figure like figure 11 as further evidence that the method works.

We agree that demonstrating the method's effectiveness as directly as possible is important. The difficulty is that, without independent information on the true geolocation and footprint size, no figure derived from our own data can establish the absolute accuracy of the aggregated estimates. What our results already do demonstrate is the internal consistency and convergence of the method: from the first to the second round the scatter is markedly reduced and the bimodal ECRO distribution collapses into a single mode (Sect. 5.4.2). Further iterations yield negligible change (lines 454–455), confirming that the applied correction renders the observation geometry self-consistent. Independent evidence suggests that the retrieved values are physically meaningful: the significant ERS-2 36.5 GHz ELON temporal trend coincides with the documented gyroscope failures (Sect. 6.2), and the retrieved *aspect ratios are consistent with the pre-launch characterisation of Bernard et al. (1993) (Sect. 6.3). We therefore prefer not to add a further figure that would show largely redundant information rather than genuinely new evidence.*

Technical Corrections:

R2-TC1: Line 177: Change "the antenna pattern used for calculating ELF is approximated as 2D Gaussian" to "the antenna pattern used for calculating ELF is approximated as **a** 2D Gaussian"

Will be corrected.

R2-TC2: Line 779: Remove extra periods following author names in the reference entry.

Well spotted! Will be corrected.