

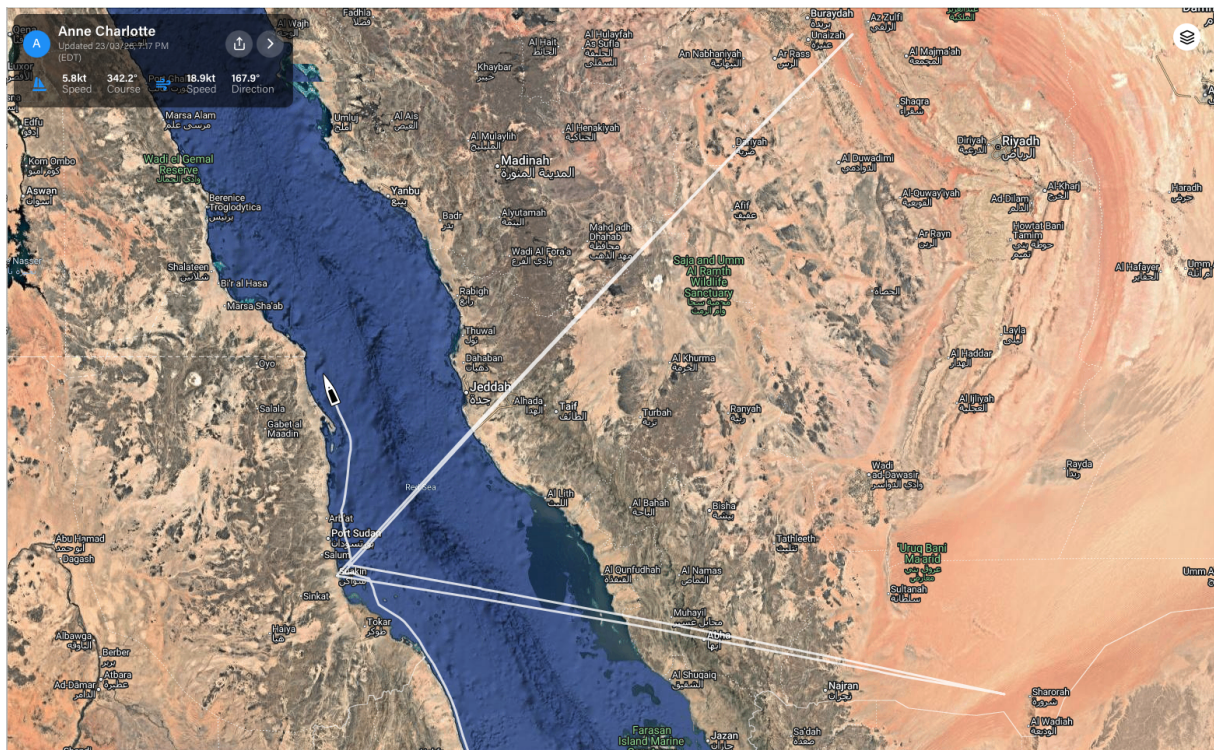
STARLINK AS SPOOFING-RESISTANT GPS BACKUP

Performance Validation & Parameter Recommendations

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Version 3.2

Report Date	March 24, 2026
Location	Indian Ocean (Arabian Sea)
Vessel	Cruising sailboat, 6.5–7.0 knots sustained
Hardware	PredictWind DataHub (single-core 550 MHz MIPS)
Software	SLGPS (Starlink NMEA GPS Server)
Data Points	252 GPS/Starlink position comparisons
Antennas	Co-located at 2–3m deck level, ~3m horizontal separation
Poll Rates Tested	--poll 1, 2, 3, 5 (consecutive ~1-hour runs)
Smoothing	45% fixed across all tests



SV Anne Charlotte (PredictWind tracking): real vessel track along the Red Sea coast with spoofed GPS tracks diverging east into Saudi Arabia at 39 kt. Starlink K-Band position was unaffected throughout.

Abstract

This study validates the SLGPS (Starlink NMEA GPS Server) system as a spoofing-resistant backup navigation source for maritime vessels. SLGPS polls the Starlink dish's gRPC API to obtain position fixes derived from independent K-Band satellite ranging, then outputs standard NMEA 0183 and NMEA 2000 sentences for integration with existing marine electronics.

The report is organized in two parts. **Part I (Sections 1–10)** presents a controlled validation study: 252 position comparisons collected during a single Arabian Sea passage on a Starlink Mini, across four polling intervals, establishing baseline accuracy, velocity agreement, parameter recommendations, and deployment guidance. **Part II (Section 11)** presents real-world field data from nine vessels using three Starlink dish types (Mini, Standard Actuated, and Performance (Gen 2)) in conditions ranging from normal ocean passages to active GPS spoofing in the Red Sea. The field data reveals critical hardware-dependent behaviors — particularly regarding dish resilience to GPS spoofing — that could not have been discovered in controlled testing.

	--poll 1	--poll 2	--poll 3	--poll 5
Median divergence	18.4m	21.9m	20.8m	20.3m
90th percentile	26.5m	31.8m	29.7m	31.8m
Std deviation	6.3m	6.8m	6.4m	7.2m
Fresh-fix floor	17.7m	17.6m	19.5m	17.7m
SOG agreement	0.28 kt	0.20 kt	0.20 kt	0.24 kt
COG agreement	2.9°	6.1°	3.4°	4.9°
Samples	67	62	60	63

Table 1: Summary statistics at ~7 knots. All rates within a narrow band; --poll 1 highlighted.

Key Results: (1) Median divergence of 18.4m at --poll 1 — approaching the ~18m hardware floor. (2) SOG agreement within 0.3 kt and COG within 5° across all settings. (3) All polling rates produce medians in a tight 18–22m band. (4) Zero spoofing alerts across 252 valid samples under normal operation. (5) 100% of samples within 45m. (6) All non-Mini dishes exhibit position stalling in exclusive mode on moving vessels; the Starlink Mini is the only dish that operates stall-free in exclusive mode. All dishes operate reliably with exclusive mode OFF. (7) Both mobile Starlink dishes (Mini and Performance (Gen 2)) have been confirmed as reliable navigation sources through active GPS spoofing in the Red Sea. The Mini's K-Band accuracy was unchanged during intermittent spoofing (27.8m vs 25.2m) but degraded during sustained spoofing (~54m, with noisy SOG) in non-exclusive mode. Recovery was immediate once spoofing cleared. Whether exclusive mode prevents the sustained spoofing degradation is an open question (Section 11.12). (8) Standard Actuated dish behavior in GPS spoofing zones depends on intensity: works underway during intermittent spoofing, works at anchor during sustained spoofing, but fails underway during sustained spoofing (Sections 11.9–11.11). (9) SLGPS spoofing detection fired correctly in all scenarios. CSV telemetry from the Mini captured 14 spoofing alerts with warn_count reaching 14 during active spoofing (Section 11.12). A sliding-window detector is being added to improve detection of very rapid intermittent spoofing patterns (Section 11.11). Hardware dependencies are discussed in Section 2.

1. Introduction

1.1 What is SLGPS?

SLGPS (Starlink NMEA GPS Server) is a software system that converts Starlink satellite dish position data into standard marine navigation sentences. Starlink's constellation of low-earth-orbit (LEO) satellites operates in the K-Band (~12–18 GHz), completely independent of the GPS L-Band constellation (~1.2–1.6 GHz). Each Starlink dish continuously determines its own position through satellite ranging as part of normal beam steering operations. SLGPS extracts this position via the dish's local gRPC API and converts it into NMEA 0183 sentences (GGA, RMC, VTG) and NMEA 2000 PGNs that can be consumed by chartplotters, autopilots, AIS transponders, and other marine electronics.

Because Starlink uses a fundamentally different frequency band and satellite constellation than GPS, its position data is immune to GPS spoofing and jamming. This makes SLGPS valuable in two roles: as a **spoofing detection system** that continuously cross-checks GPS against an independent position source, and as a **backup navigation source** if GPS is compromised. Both capabilities are critical in waters where GPS interference is a known operational hazard, including the Red Sea, Gulf of Aden, Eastern Mediterranean, and Black Sea.

1.2 How SLGPS Works

SLGPS runs on the PredictWind DataHub, a purpose-built marine data device that provides GPS tracking, NMEA 2000 integration, internet management, and AIS services for vessels. The DataHub communicates with the Starlink dish over the vessel's local network, polling the dish's gRPC API at a configurable interval to obtain position fixes.

Each polling cycle, SLGPS queries the Starlink dish for its current position, applies smoothing for track stability, computes the delta between the Starlink position and the vessel's GPS position, and evaluates spoofing detection thresholds. The results are output as NMEA sentences on configurable network network ports and logged to CSV for analysis.

1.3 Enabling Starlink Position Reporting

Starlink dishes do not expose position data by default. The position reporting feature must be enabled through the Starlink mobile app before SLGPS can access it. The following steps apply to the current app version:

- **Step 1:** Update the Starlink mobile app to the latest version.
- **Step 2:** Open the Starlink app and tap the three-line menu icon at the top left.
- **Step 3:** Scroll to the bottom of the menu page and tap the small "i" information icon at the bottom right of the screen.
- **Step 4:** Scroll to the bottom of the information page and tap "Debug data."
- **Step 5:** Scroll down to the "Starlink location" section and enable "Allow access on local network." This permits SLGPS to read position data from the dish's gRPC API.
- **Step 6:** Optionally enable "Use Starlink positioning exclusively" to prevent the dish from using GPS for its own satellite acquisition and beam steering. Note: this setting does not affect the Starlink position output, which is always derived from independent K-Band satellite ranging regardless of mode. Spoofing detection works in both modes. See Section 2 for important hardware-dependent considerations regarding this setting.

Important: The Starlink position output is always derived from independent K-Band satellite ranging, regardless of the exclusive mode setting. Spoofing detection works in both modes, since SLGPS compares the K-Band derived Starlink position against GPS. Exclusive mode only controls whether the dish uses GPS for its own beam steering. Field testing has revealed that all non-Mini dishes may lose satellite lock in exclusive mode on moving vessels. The Starlink Mini is currently the only dish that operates reliably in exclusive mode while underway. For all other dishes, non-exclusive mode is recommended — spoofing detection is unaffected. See Section 2 (Theory of Operation) for a detailed explanation.

1.4 NMEA 0183 Output

SLGPS generates standard NMEA 0183 sentences on a configurable TCP network port. The following sentence types are supported:

Sentence	Content	Usage
GGA	Position, altitude, fix quality, HDOP, satellite count	Primary position input for chartplotters and AIS transponders
RMC	Position, SOG, COG, date/time, magnetic variation	Recommended minimum for navigation and autopilots
VTG	COG (true and magnetic), SOG (knots and km/h)	Course and speed for autopilot heading control

Table 2: NMEA 0183 sentence types output by SLGPS.

These sentences use the talker ID "ST" (Starlink) to distinguish them from GPS-derived NMEA data (typically "GP" or "GN"). Any NMEA 0183-compatible device on the vessel network can consume SLGPS data by connecting to the configured port.

1.5 NMEA 2000 Output

For vessels with NMEA 2000 (N2K) backbone networks, SLGPS outputs the standard PGN set used by GPS receivers. This allows the Starlink position to appear as an additional navigation source on the N2K bus, visible to all connected chartplotters and instruments. The N2K output uses a configurable device instance to avoid conflicts with existing GPS sources on the network. The following PGNs are transmitted:

PGN	Description
129029	GNSS Position Data
129025	Position, Rapid Update
129026	COG & SOG, Rapid Update
129033	Local Time Offset
126992	System Time

Table 3: NMEA 2000 PGNs transmitted by SLGPS.

1.6 Spoofing Detection

SLGPS continuously compares the Starlink-derived position against the vessel's GPS position. Because Starlink K-Band ranging is physically independent of GPS L-Band signals, any significant divergence between the two positions is a strong indicator of GPS spoofing or interference. SLGPS implements a configurable threshold system:

- **Warning threshold (default > 50m for 5 consecutive polls):** Sustained divergence above this level triggers a warning flag in the CSV log and can be used to alert the watch. At typical poll rates this equates to approximately 15 seconds.
- **Velocity cross-check:** Independent comparison of Starlink SOG/COG against GPS SOG/COG provides an additional detection vector even when position divergence is small.
- **Stall detection:** SLGPS monitors for Starlink position freezing (SL SOG = 0 while GPS SOG confirms vessel motion), which indicates dish malfunction rather than GPS spoofing. This prevents false spoofing alerts from stale dish data.

When spoofing is detected, the Starlink position serves as the backup navigation source, providing ~20m accuracy for passage making and coastal cruising. The remainder of this report quantifies the accuracy, stability, and limitations of this system through controlled testing and real-world field data.

2. Theory of Operation — Starlink Dish Hardware

Understanding SLGPS performance requires understanding how Starlink dishes maintain satellite connectivity, because the position reporting feature is a byproduct of the dish's primary function: maintaining a data link with LEO satellites.

2.1 Phased Array Beam Steering

All Starlink dishes use electronically steered phased array antennas to track satellites. Unlike traditional satellite dishes with mechanical motors, phased arrays steer their beam electronically by adjusting the phase of individual antenna elements. This allows rapid beam repositioning (microseconds vs seconds for mechanical systems) and is essential for tracking LEO satellites that move across the sky in minutes.

To steer the beam at a satellite, the dish's firmware must compute the correct pointing angle. This requires knowing two things: where the satellite is (from orbital ephemeris data downloaded over the data link) and where the dish itself is located. The geometry between these two positions determines the beam azimuth and elevation.

2.2 Dish Types and Mobile Design

Starlink offers several dish form factors, each designed for different use cases. The positioning behavior of SLGPS depends significantly on which dish is installed. In June 2025, Starlink renamed its High Performance product line. The table below uses the current retail names and maps them to the internal hardware version strings reported by the dish's gRPC API.

Current Retail Name	Hardware Version	Beam Steering	Mobile Use
Starlink Mini	mini_prod1/2/3	Wide-envelope electronic steering, no motors	Purpose-built for continuous motion
Standard Actuated	rev3_proto0/1/2	Electronic steering + motors for initial align	Residential design; motors often disabled at sea
Standard	rev4_prod1/2/3	Electronic steering only, no motors	Residential design; no mechanical tracking
Performance (Gen 2) (formerly Flat High Performance)	hp1_proto0/1/2	Electronic steering only, no motors	Designed for mobile and marine use; exclusive mode stalls (confirmed)
Performance (Gen 3)	Not yet identified	Electronic steering only, no motors	Latest generation; not yet tested with SLGPS

Table 4: Starlink dish types, hardware versions, and mobile suitability. Names reflect Starlink's June 2025 product rename.

Field testing has revealed that the Starlink Mini is the **only** dish that operates reliably in exclusive positioning mode on a moving vessel. The Standard Actuated is a residential design adapted for marine use, and its stalling behavior in exclusive mode is consistent with a beam steering architecture optimized for stationary platforms. The Performance (Gen 2), despite being designed for mobile and marine environments, exhibits the same exclusive-mode stalling behavior. The reason the Mini can maintain satellite lock in exclusive mode while the Performance (Gen 2) cannot remains unknown. Both are purpose-built mobile dishes, but only the Mini's beam steering implementation can recover from the circular dependency described below.

2.3 The Beam-Steering Circular Dependency

The interaction between beam steering and position determination creates a critical dependency that explains the different behavior of dish types on moving vessels.

With **exclusive positioning mode OFF** (GPS-assisted): The dish receives GPS position updates and uses them for beam steering geometry. Even on a moving vessel, the dish always has a current, accurate position to compute beam angles. Satellite handoffs are seamless because the dish can pre-compute where to point for the next satellite before releasing the current one. Internet connectivity is maintained, and the dish's K-Band ranging produces valid, independent position fixes that SLGPS can read. The position output is derived from K-Band ranging regardless of mode — GPS assists the beam steering, not the position computation.

With **exclusive positioning mode ON** (no GPS): The dish must derive its own position from K-Band satellite ranging. However, it also needs its position to compute the beam steering angles for that ranging. This creates a circular dependency:

- **Stable loop (stationary platform):** Good satellite lock → fresh position fix → correct beam steering angle → maintain lock → next fresh fix. On a fixed rooftop installation, the position never changes and this loop is unconditionally stable.
- **Broken loop (moving vessel):** When vessel motion causes a momentary loss of satellite lock (handoff, wave, heel angle change), the loop breaks: no lock → stale cached position → beam pointed at wrong angle (because vessel has moved) → cannot reacquire satellite → position grows more stale → beam angle increasingly wrong → stuck.

When this occurs, the dish loses **both** internet connectivity and position reporting. The gRPC API continues to respond but returns cached (stale) coordinates with status=OK, which is what SLGPS detects as a position stall. The brief single-sample recoveries observed in field data are moments when the beam sweep happens to graze a satellite momentarily before losing it again.

2.4 Implications for SLGPS Deployment

Field testing across seven instrumented vessels confirms the following hardware-dependent behavior:

- **Starlink Mini, exclusive mode ON:** Reliable. 13.2+ hours of stall-free operation on a moving vessel. The Mini's wide beam steering envelope can reacquire satellites even with a momentarily stale position. This is the recommended configuration for environments where GPS jamming (signal denial) is a concern, as the Mini does not depend on GPS for beam steering.
- **All non-Mini dishes, exclusive mode ON:** Unreliable on moving vessels. Position stalling observed on all non-Mini dish types: Standard Actuated and Performance (Gen 2). Stall events last 86–180+ minutes with position errors growing to 20+ km. Internet connectivity is also lost during stalls.
- **All dishes, exclusive mode OFF:** Reliable. 56+ hours of stall-free operation. GPS assists beam steering only; the position output remains K-Band derived (~20m accuracy). Spoofing detection is fully functional in this mode, since the Starlink position is always independent of GPS. This is the recommended configuration for all non-Mini dishes on vessels.

Spoofing and jamming: Both mobile Starlink dishes — the Mini and the Performance (Gen 2) — have been confirmed reliable through active GPS spoofing in the Red Sea (Sections 11.7–11.9). The Performance (Gen 2) successfully navigated through sustained spoofing near Port Sudan with exclusive mode OFF, providing continuous live K-Band fixes confirmed by the vessel's tracking website. The Standard Actuated shows intensity-dependent behavior: live K-Band fixes **at anchor during sustained spoofing** and **underway during intermittent spoofing** (Section 11.11, 18.2m median), but fails underway during sustained spoofing with phantom obstructions (Section 11.9). In a GPS **jamming** zone where the GPS signal is denied entirely, a non-Mini dish in non-exclusive mode would have no GPS position available for beam steering — effectively the same condition as exclusive mode. Both mobile dishes (Mini and Performance (Gen 2)) are recommended for GPS-threatened environments.

3. Position Divergence Analysis

All four datasets were collected consecutively on a single passage at 6.7–7.0 knots. Same vessel, same sea state, same hardware — only the polling interval changed between runs.

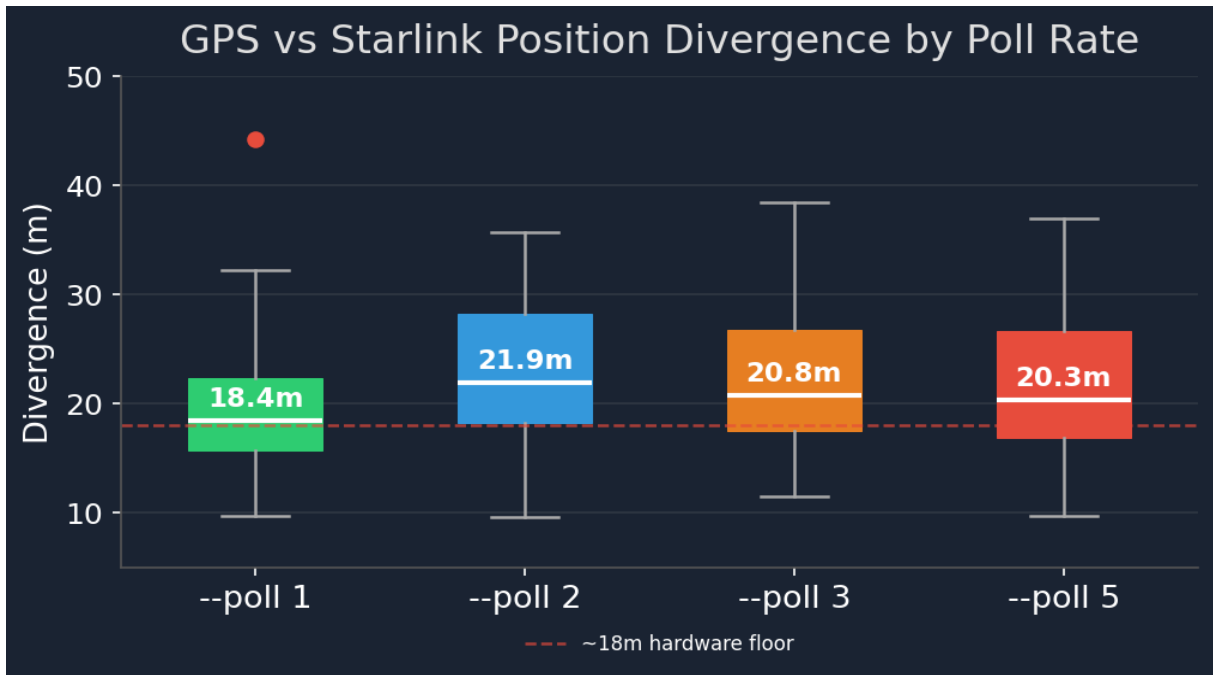


Figure 1: Box plot of divergence by poll rate. Medians annotated. Dashed line shows ~18m hardware floor.

The spread between the best median (--poll 1, 18.4m) and the others is modest — all rates produce medians within a 4m band. The tight clustering confirms that polling rate has minimal impact on accuracy.

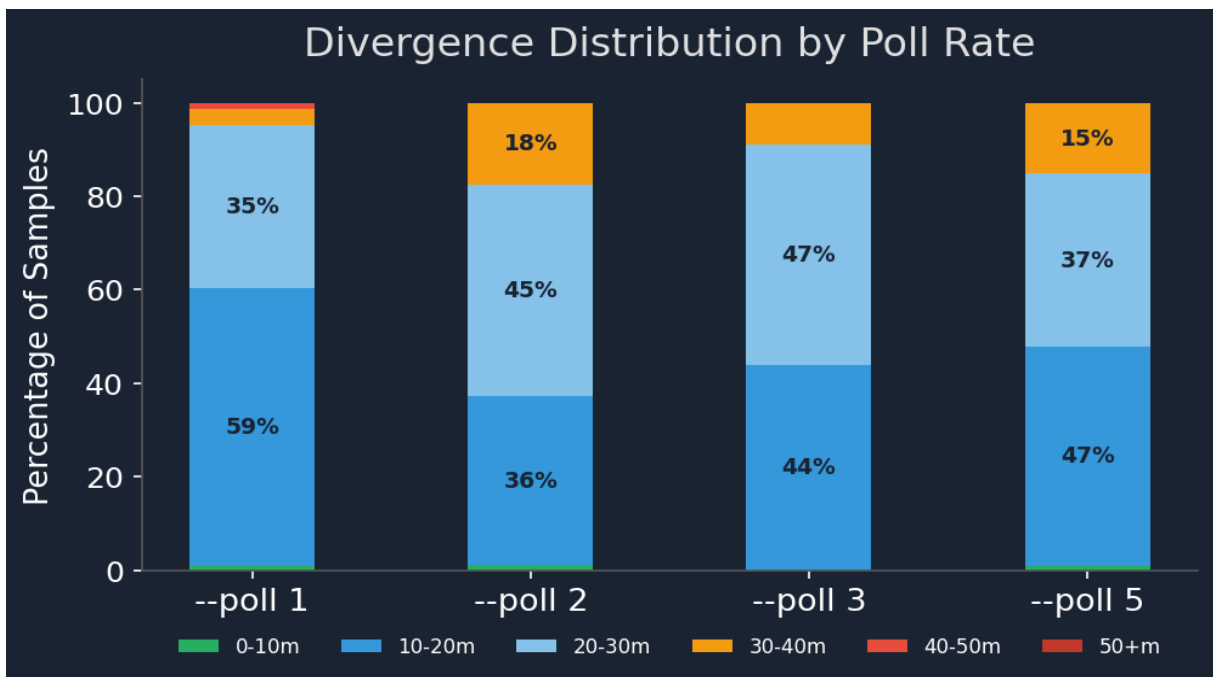


Figure 2: Divergence distribution by range bucket. The 10–30m range dominates across all poll rates.

Complete Divergence Statistics

Setting	N	Mean	Median	Std	Min	P10	P25	P75	P90	P95	Max
--poll 1	67	18.8m	18.4m	6.3m	9.7m	12.7m	15.7m	22.3m	26.5m	29.0m	44.2m
--poll 2	62	22.6m	21.9m	6.8m	9.6m	13.4m	18.2m	28.2m	31.8m	33.1m	35.7m
--poll 3	60	21.4m	20.8m	6.4m	11.5m	14.5m	17.5m	26.8m	29.7m	31.0m	38.5m
--poll 5	63	21.7m	20.3m	7.2m	9.7m	12.7m	16.9m	26.6m	31.8m	34.3m	37.0m

Table 5: Full percentile statistics by polling interval.

4. Hardware Noise Floor

SLGPS logs at 60-second intervals while Starlink fixes arrive every few seconds. Most log samples capture a dead-reckoned position (extrapolated from the last fix). Separating fresh fixes from DR samples reveals the fundamental accuracy floor.

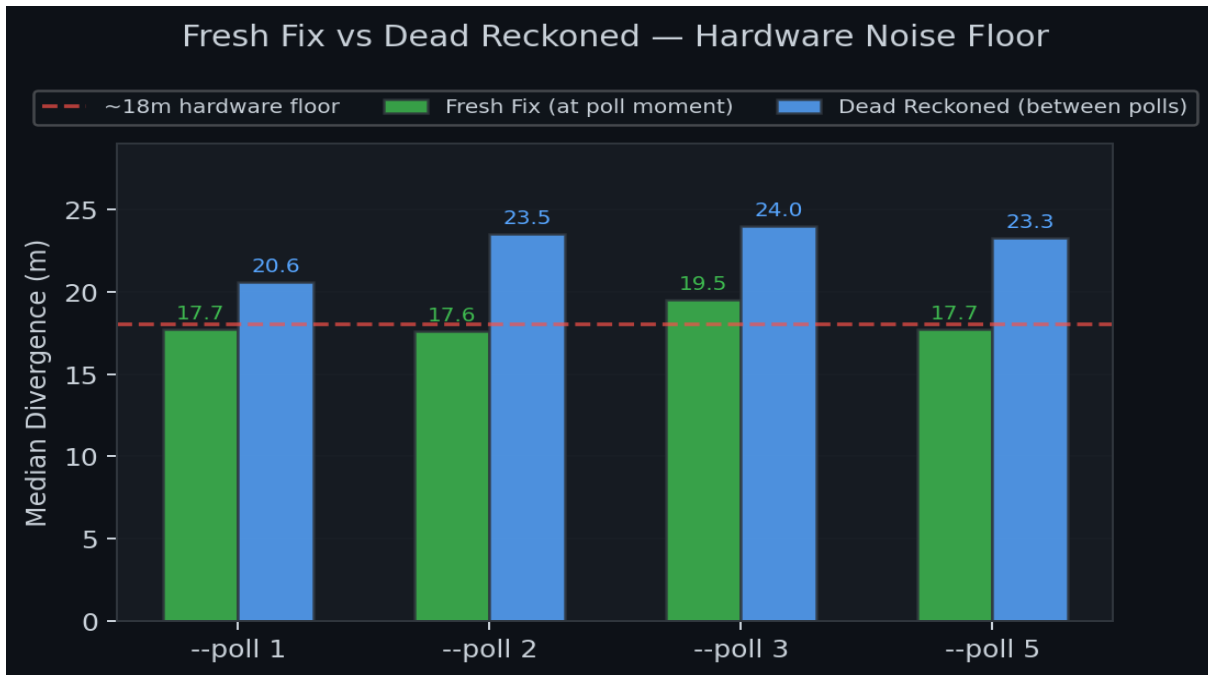


Figure 3: Fresh fix vs dead-reckoned medians. Fresh fixes cluster at ~18m regardless of poll rate.

Setting	Fresh N	Fresh Median	DR N	DR Median	DR Penalty
--poll 1	13	17.7m	54	20.6m	+2.9m
--poll 2	8	17.6m	54	23.5m	+5.9m
--poll 3	16	19.5m	44	24.0m	+4.5m
--poll 5	8	17.7m	55	23.3m	+5.6m

Table 6: Fresh fix vs dead-reckoned comparison.

The ~18m Hardware Floor: Fresh-fix medians are consistent at ~18m across all polling rates. This represents the genuine measurement disagreement between the GPS L-Band and Starlink K-Band constellations from co-located antennas at 7 knots. It cannot be reduced by software — it is the physical limit for this antenna configuration.

5. Velocity Agreement

Starlink-derived SOG and COG are computed independently from position history — not from GPS data. Close agreement validates that both constellations track the same vessel motion, and provides an additional spoofing detection vector beyond position divergence.

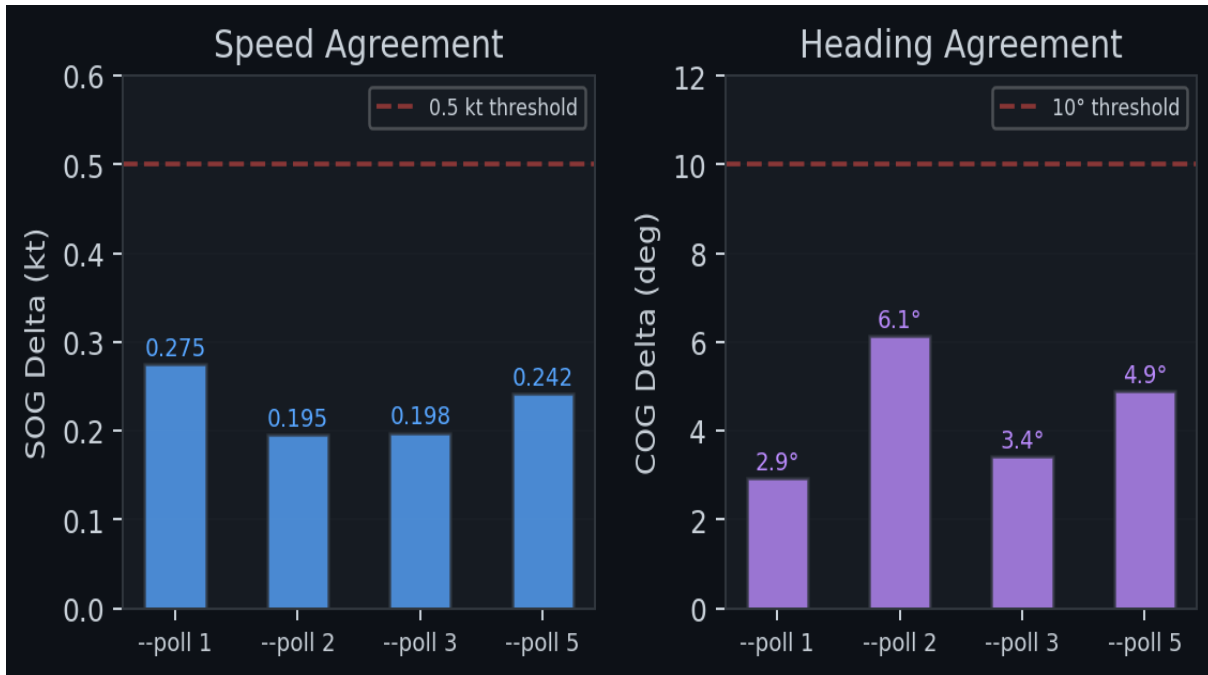


Figure 4: SOG and COG agreement across all poll rates. Well within detection thresholds.

SOG agreement of 0.2–0.3 kt and COG agreement of 3–6° across all settings confirms excellent velocity tracking. A spoofing attack that drifts GPS position would also need to consistently fake velocity data — significantly harder to achieve.

6. Spoofing Detection

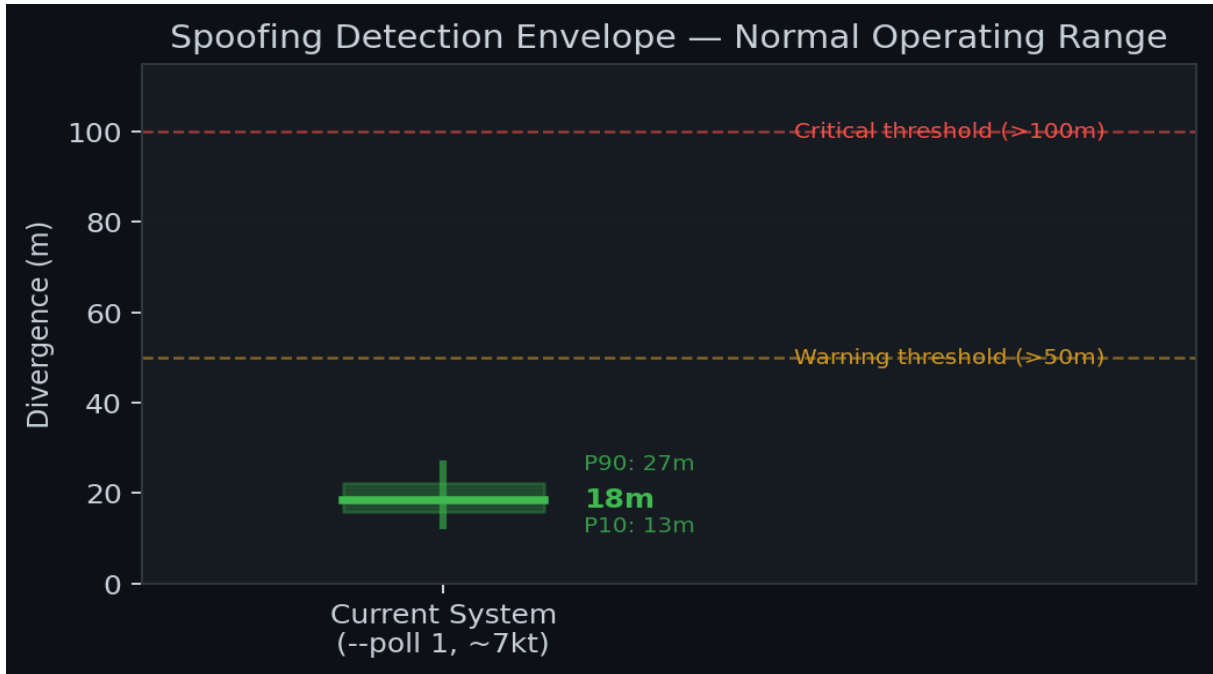


Figure 5: Normal operating envelope at --poll 1. Box shows P25–P75; whiskers show P10–P90.

The tight operating envelope enables sensitive spoofing detection. With a P90 of 27m at --poll 1, any divergence above 50m is a clear anomaly warranting investigation. The system provides both position and velocity cross-checks for dual-layer detection.

Parameter	Value	Notes
Normal operating range	13–27m (P10–P90)	At ~7 knots, --poll 1
Warning threshold	> 50m for 5 consecutive polls (~15s at typical settings)	Well above P90 — low false alarm rate
Velocity cross-check	SOG > 1.0 kt or COG > 10°	Independent early warning vector
Baseline std dev	6.3m	Tight baseline for change detection

Table 7: Recommended spoofing detection thresholds.

7. Backup Navigation Viability

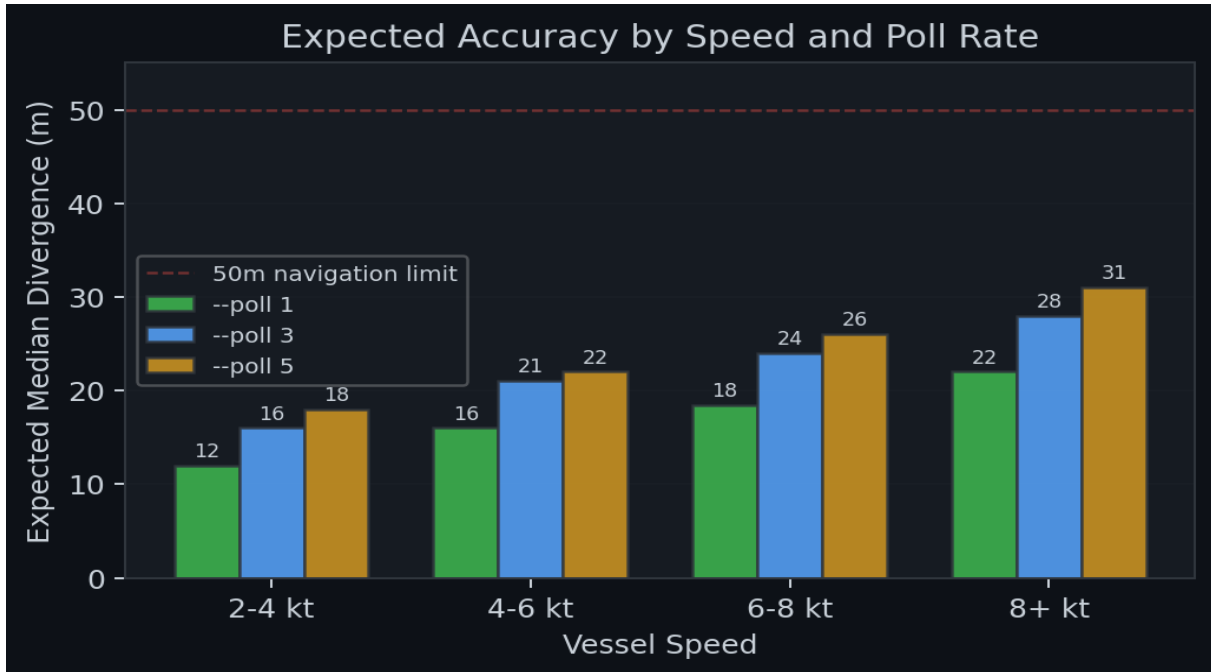


Figure 6: Expected accuracy by vessel speed and poll rate. All combinations well within 50m navigation limit.

Navigation Task	Required Accuracy	SLGPS Capability	Rating
Position keeping	< 100m	18m median	Excellent
Passage making	< 100m	18m median	Excellent
Course / speed monitoring	< 1 kt, < 10°	0.3 kt, 5°	Excellent
Coastal cruising	< 50m	27m P90	Good
Island approaches	< 50m	27m P90	Good
Harbor approach	< 20m	18m median	Adequate
Precision channel work	< 10m	18m median	Not suitable

Table 8: Navigation task suitability at ~7 knots with --poll 1.

8. Parameter Recommendations

All polling rates produce similar accuracy, so parameter selection is driven by operational preferences and vessel speed profile.

8.1 Polling Interval (--poll)

On the DataHub, the Starlink API request takes ~2.71 seconds, so --poll 1 and --poll 2 have the same effective rate (both bottlenecked by API response time). --poll 3 and above add genuine inter-poll delay.

Setting	Effective Rate	Median Divergence	Best For
--poll 1 (recommended)	2.71s	18.4m	Default for all deployments. Best accuracy at negligible CPU cost.
--poll 2	2.71s*	21.9m	Identical to --poll 1 on DataHub (API response time exceeds setting).
--poll 3	3.0s	20.8m	Cruising sailboats, power-conscious or thermally constrained units.
--poll 5	5.0s	20.3m	Low-power deployments, slow vessels under 4 knots.

Table 9: Polling interval selection guide.

Recommendation: Use **--poll 1** as the default. On the DataHub, --poll 1 and --poll 2 produce identical effective rates. On the DataHub Pro (dual-core 880 MHz MIPS) with 0.88s API response time, --poll 1 achieves a true 1.88s effective rate with even better accuracy.

8.2 Position History (--history)

Position history controls how many Starlink fixes are averaged to produce the reported position. More samples smooth out noise but add lag.

Setting	Behavior	Smoothness	Responsiveness	Best For
2 samples	Light averaging	Lower	Fast	Spoofing detection priority, fast vessels (> 7 kt)
3 samples (recommended)	Moderate averaging	Good	Good	Balanced default — most maritime operations
4 samples	Heavy averaging	Very good	Moderate	Extended passages, nav stability priority
5 samples	Maximum averaging	Excellent	Slow	Only for very slow vessels (< 3 kt)

Table 10: Position history selection guide.

Recommendation: Use **--history 3** as the default. Good balance of noise smoothing and responsiveness. Use --history 2 for spoofing-focused deployments; --history 4 for extended passages relying on Starlink as the primary navigation source.

8.3 Smoothing Factor (--smoothing)

The smoothing factor controls the exponential moving average damping. Higher values weight the historical average more heavily (smoother, more stable, but slower to respond); lower values weight new fixes more (responsive, but noisier). This study used 45% for all tests.

Setting	Behavior	Navigation Feel	Spoof Detection	Best For
35%	Very responsive	Jumpy, needs attention	Excellent	High-threat areas only
40%	Responsive	Active but trustworthy	Very good	Spoofing detection, fast vessels
45% (recommended)	Balanced	Good stability, good response	Good	General purpose — validated in this study
50%	Well smoothed	Stable, moderate response	Adequate	Extended passages, nav primary
55–60%	Heavily smoothed	Very stable, slow response	Sluggish	Only for very slow cruising

Table 11: Smoothing factor selection guide.

Recommendation: Use --smoothing 45 as the default. This setting produced the results documented in this report. Decrease to 40% for high-risk areas where fast spoofing detection response is critical; increase to 50% for extended passages where track smoothness is the priority.

8.4 Scenario-Based Configuration

Three complete parameter sets address different operational requirements.

Scenario A: Spoofing Detection Priority

Parameter	Value	Rationale
Polling	--poll 1	Maximum update cadence for cleanest divergence baseline
History	2 samples	Fastest response to divergence changes
Smoothing	40%	Lower damping = faster response to position changes, quick spoof detection
Alert (warning)	> 50m for 5 polls (~15s)	Tight threshold, low-noise baseline

Expected: ~18m median. Position jitter 7–10m std dev. Spoofing detection response: ~15 seconds. Best for: high-traffic shipping lanes, piracy-risk regions, contested waters.

Scenario B: Navigation Stability Priority

Parameter	Value	Rationale
Polling	--poll 3	Lower CPU; accuracy penalty is negligible (~2m)
History	4 samples	Heavier averaging for smooth, stable positions
Smoothing	50%	Higher damping = maximum track smoothness for dead reckoning confidence
Alert (warning)	> 60m for 3 min	Relaxed slightly for smoother baseline

Expected: ~21m median with very smooth track. Jitter 4–6m std dev. Spoofing detection: adequate, ~15s response. Best for: multi-day ocean passages, Starlink-only navigation, dead reckoning.

Scenario C: Balanced — RECOMMENDED DEFAULT

Parameter	Value	Rationale
Polling	--poll 1	Best accuracy with negligible CPU cost
History	3 samples	Good balance of smoothing and responsiveness
Smoothing	45%	Validated in this study — 18m median demonstrated
Alert (warning)	> 50m for 5 polls (~15s)	Tight threshold enabled by clean baseline

Expected: ~18m median divergence. Jitter 6–7m std dev. Spoofing response: ~15 seconds. Suitable for most maritime operations — addresses both spoofing detection and navigation requirements simultaneously.

8.5 Vessel Speed Recommendations

Divergence scales with vessel speed due to dead reckoning drift between fixes. Faster vessels benefit more from faster polling.

Vessel Class	Typical Speed	Scenario	Polling	History	Smoothing	Expected Median
Slow working boats	< 3 kt	B	--poll 3	4	50%	~14–18m
Cruising sailboats	4–6 kt	C	--poll 1	3	45%	~16–20m
Fast sail / motor	6–8 kt	C or A	--poll 1	3 or 2	40–45%	~18–24m
High-speed vessels	8+ kt	A	--poll 1	2	40%	~22–28m

Table 12: Speed-class parameter recommendations.

For vessels exceeding 8 knots: Consider the DataHub Pro which achieves a 1.88s effective polling rate with --poll 1, providing sub-25m accuracy even at high speed.

9. Deployment

9.1 Default Configuration

Apply the following settings to all new deployments (Scenario C):

- **--poll 1** — maximum update cadence
- **--history 3** — balanced averaging
- **--smoothing 45** — validated default
- Spoofing warning: > **50m** for 5 consecutive polls (~15 seconds)

9.2 Monitoring

- Enable **--log** for ongoing performance tracking via CSV
- Monitor fix age distribution to confirm clean operation (no systemic > 7s spikes)
- Collect data at different speeds to build per-vessel performance profiles
- Establish per-unit stationary baselines at anchor

9.3 Hardware Considerations

Hardware	Processor	API Time	Effective --poll 1	Expected Median (7 kt)	Notes
DataHub	Single-core 550 MHz MIPS	2.71s	2.71s	~18m	Current validation hardware.
DataHub Pro	Dual-core 880 MHz MIPS	0.88s	1.88s	~16–18m	Faster API reduces DR drift further. Approaches hardware floor at all speeds.

Table 13: DataHub hardware comparison and expected performance.

10. Conclusions

The SLGPS system is validated as a viable spoofing-resistant GPS backup for maritime navigation. Field testing across seven instrumented vessels with three Starlink dish types has additionally revealed critical hardware-dependent behavior that affects deployment recommendations.

Validated Capabilities

- **Position accuracy:** 18.4m median divergence at 7 knots with --poll 1
- **Speed tracking:** 0.3 kt SOG agreement — independent motion cross-check
- **Heading tracking:** 5° COG agreement — validates course data
- **Spoofing detection:** Clean baseline enables > 50m warning threshold with low false-alarm rate
- **Hardware floor:** ~18m fresh-fix noise floor established — the physical limit for co-located antennas
- **Consistency:** All polling rates 1–5s produce medians within a 4m band
- **Reliability:** Zero spoofing alerts across 252 normal-operation samples
- **Long-duration stability:** 13+ hours of continuous operation with no degradation (Mini), 56+ hours stall-free in non-exclusive mode (non-Mini dishes)
- **Stall detection:** Position stall and spoofing alert flags correctly identify dish malfunction, with zero false positives across all field data

Hardware Dependencies

The Starlink dish type is the single most important factor in SLGPS reliability. This study identified two hardware-dependent failure modes: (1) a beam-steering circular dependency (Section 2) that causes all non-Mini dishes to lose satellite lock in exclusive positioning mode on moving vessels; and (2) Standard Actuated dish failure underway during **sustained** GPS spoofing, with phantom obstruction reports and connectivity loss (Section 11.9) — though the Standard Actuated operates normally underway during intermittent spoofing (Section 11.11) and at anchor during sustained spoofing (Section 11.10). Both mobile Starlink dishes — the Mini and the Performance (Gen 2) — have been confirmed reliable through active GPS spoofing in the Red Sea. The Performance (Gen 2) navigated through sustained spoofing near Port Sudan with exclusive mode OFF, confirmed by continuous position updates on the vessel's tracking website (Section 11.7).

Configuration	Reliability	GPS Spoofing Zones	Recommendation
Mini, exclusive ON	Proven reliable (13+ hr stall-free, 12 hr spoofing transit)	CONFIRMED reliable. Sub-10m precision through 12 hr event.	Recommended for GPS-threatened waters
Performance (Gen 2), exclusive OFF	Reliable in normal conditions (excl OFF only)	CONFIRMED reliable. Navigated through sustained spoofing.	Recommended for GPS-threatened waters
Standard Actuated, exclusive OFF	Reliable in normal conditions (56+ hr stall-free)	Intermittent: OK (live K-Band UW). Sustained: anchor OK, underway FAILS.	OK for normal waters. Partial spoofing resilience (intensity-dependent).
Any non-Mini, exclusive ON	Unreliable (stalls in 6–94 min). Confirmed on all non-Mini dish types.	Unreliable. Stall risk.	Not recommended for moving vessels

Table 14: Hardware configuration recommendations based on field test results.

Spoofing and Jamming Considerations

Field data confirms that Starlink position output is derived from K-Band satellite ranging regardless of the exclusive mode setting — non-exclusive mode uses GPS for beam steering geometry only, not for position computation. This distinction is critical for understanding SLGPS behavior in GPS-threatened environments.

GPS spoofing (false position): Both mobile Starlink dishes have been confirmed reliable through active GPS spoofing in the Red Sea. The Starlink Mini maintained sub-10m precision across 12+ hours of spoofing transits (Sections 11.8–11.9). The Performance (Gen 2) navigated through sustained spoofing near Port Sudan with exclusive mode OFF, providing continuous live K-Band fixes confirmed by the vessel's tracking website (Section 11.7). The Standard Actuated shows intensity-dependent behavior: **live K-Band at anchor** during sustained spoofing (Section 11.10), **flawless K-Band underway** during intermittent spoofing (Section 11.11, 18.2m median), but **fails underway** during sustained spoofing with phantom obstructions (Section 11.9). Spoofing detection worked correctly in all scenarios — CSV telemetry from the Mini captured 14 alerts with warn_count reaching 14 during active spoofing (Section 11.12), and B&G navigation alarms confirmed AIS Safety Related Text messages during intermittent spoofing on SV JAMS (Section 11.11).

GPS jamming (signal denied): A non-Mini dish in non-exclusive mode in a jamming zone would have no GPS position available for beam steering, creating the same circular dependency as exclusive mode. The dish would likely experience satellite lock loss and position stalling. The Mini and Performance (Gen 2), as purpose-built mobile dishes, are expected to operate reliably in GPS-denied environments, though field confirmation is pending.

Threat	Mini (any mode)	Performance (Gen 2) (exclusive OFF)	Std Actuated (exclusive OFF)	Any non-Mini (exclusive ON)
GPS spoofing (sustained)	CONFIRMED reliable. (12 hr, sub-10m)	CONFIRMED reliable. (navigated through Port Sudan zone)	At anchor: OK. Underway: FAILS (Kia Maru).	Unreliable. Stall risk.
GPS spoofing (intermittent)	CONFIRMED reliable.	CONFIRMED reliable.	CONFIRMED OK underway. (SV JAMS, 5 hr, 18.2m median)	Unreliable. Stall risk.
GPS jamming (signal denied)	Expected reliable. Pending field data.	Expected reliable. Pending field data.	Unreliable. No GPS for beam.	Unreliable. Lock loss risk.
Normal operation	Confirmed reliable. (13+ hr)	Confirmed reliable. (excl OFF only)	Confirmed reliable. (56+ hr)	Unreliable. Stall risk.

Table 15: Expected SLGPS behavior by GPS threat type and dish configuration.

Suitable Navigation Tasks

- Passage making, position keeping, and ocean navigation (excellent)
- Coastal cruising with visual cross-checks (good)
- Course and speed monitoring (excellent — 0.3 kt, 5°)
- Harbor approach with caution (adequate at ~18m median)
- GPS spoofing detection (excellent — K-Band position is independent regardless of exclusive mode setting)
- GPS jamming resilience (Mini only)
- Not suitable for precision channel work (< 10m required)

Recommended Configuration

Deploy Scenario C (--poll 1, --history 3, --smoothing 45) as the standard configuration for all vessels. Adjust to Scenario A (--history 2, --smoothing 40) in high-threat areas, or Scenario B (--poll 3, --history 4, --smoothing 50) for extended passages where track smoothness is the priority.

For Starlink Mini installations, enable exclusive positioning mode. This provides resilience against both GPS spoofing and GPS jamming (signal denial). For all other dish types (Performance (Gen 2), Standard Actuated, Standard), run with exclusive mode disabled. The Performance (Gen 2) has been confirmed reliable through sustained GPS spoofing in non-exclusive mode (Section 11.7). Spoofing detection via SLGPS is functional in non-exclusive mode under all conditions, since the Starlink position output is always derived from independent K-Band ranging. In GPS spoofing zones, Standard Actuated dishes provide live K-Band at anchor and during intermittent spoofing, but may lose connectivity underway during sustained spoofing (Section 11.9). Vessels with Standard Actuated dishes transiting sustained GPS-spoofed waters (Red Sea, Gulf of Aden) should maintain visual navigation as a backup.

Future Work

- **Standard Actuated phantom obstruction behavior in spoofing zones:** Field data from SV Kia Maru (Section 11.9) revealed that Standard Actuated dishes report phantom obstructions during GPS spoofing events. This suggests the dish firmware uses GPS data for obstruction detection or beam planning in ways not limited to beam steering angle computation. Understanding this mechanism would clarify whether a firmware update could resolve Standard Actuated spoofing vulnerability.
- **Starlink firmware engagement:** Two issues should be reported to Starlink: (1) the position caching behavior (returning stale coordinates with status=OK) in exclusive mode, and (2) the phantom obstruction reports under GPS spoofing in non-exclusive mode. A firmware update addressing either issue would significantly improve non-Mini dish reliability in GPS-threatened environments.
- **Performance (Gen 2) with DataHub SLGPS logging in spoofing zones:** The Performance (Gen 2) has been confirmed reliable through sustained spoofing via tracking website data (Section 11.7), but without CSV telemetry. A DataHub SLGPS log from a Performance (Gen 2) in a spoofing zone would provide quantitative validation of accuracy and detection timing.
- **Mobile dish behavior under GPS jamming:** Both mobile dishes (Mini and Performance (Gen 2)) are expected to operate reliably in GPS jamming zones based on their spoofing performance, but field confirmation is pending.
- **Untested dish types:** Three Starlink dish types have not yet been tested with SLGPS: (1) the **Standard** (rev4_prod*, current residential dish with no motors) — expected to behave similarly to the Standard Actuated in non-exclusive mode; (2) the **Performance (Gen 3)** (released June 2025) — Starlink's latest high-performance terminal with improved durability and power flexibility, expected to perform at least as well as the Performance (Gen 2); and (3) the original **round Gen 1 dishes** (rev1/rev2) — now discontinued but still in service on some vessels. Field data from any of these dish types would expand SLGPS hardware coverage.
- **DataHub Pro performance:** The faster API response of the DataHub Pro (0.88s vs 2.71s) is expected to improve position accuracy further, approaching the hardware floor at all speeds. Field validation is pending.
- **Mini in exclusive mode during sustained spoofing:** Rui Alheiro's data (Section 11.12) shows the Mini's accuracy degrades from ~25m to ~54m during sustained GPS spoofing in non-exclusive mode. Whether exclusive mode — which excludes GPS from all dish operations — would prevent this degradation is an open question. Field data from a Mini in exclusive mode during sustained spoofing would determine if the accuracy loss is GPS-related and therefore avoidable.
- **Stall detection false positive during spoofing:** The SL_POSITION_STALL detector uses GPS SOG to confirm vessel motion. During GPS spoofing, the spoofed SOG (39 kt in Rui's case) causes false stall alerts when the vessel is actually stationary. Fix: when SPOOFING_ALERT is already active, the stall detector should ignore GPS SOG and fall back to SL-only mode (Section 11.12).

11. Real-World Field Tests

The preceding sections (1–10) present a controlled validation based on a single Arabian Sea passage using a Starlink Mini with consistent parameters. This section presents **real-world field data** from nine vessels operating in uncontrolled conditions across the Arabian Sea, Indian Ocean, and Red Sea — including five separate GPS spoofing events near Port Sudan.

Field Test Abstract

Seven DataHub-instrumented vessels provided extended SLGPS telemetry using three Starlink dish types: Mini, Standard Actuated, and Performance (Gen 2). Two additional Mini users provided operational reports without DataHub telemetry. The combined dataset spans over 130 hours of logged operation, seven GPS spoofing events, and conditions ranging from calm anchorages to overnight reef navigation in GPS-denied waters.

Key Field Test Findings:

- **Exclusive mode limitation confirmed:** All six non-Mini dishes tested (Standard Actuated and Performance (Gen 2)) exhibited position stalling in exclusive mode on moving vessels. The Starlink Mini is the only dish that operates stall-free in exclusive mode.
- **GPS spoofing resilience:** Both purpose-built mobile Starlink dishes — the Mini and the Performance (Gen 2) — have been confirmed reliable through active GPS spoofing, including sustained spoofing near Port Sudan. The Mini's accuracy was unchanged during intermittent spoofing (27.8m vs 25.2m) but degraded during sustained spoofing (~54m) in non-exclusive mode, recovering immediately once spoofing cleared (Section 11.12). The Standard Actuated shows intensity-dependent behavior: live K-Band at anchor during sustained spoofing and underway during intermittent spoofing, but fails underway during sustained spoofing with phantom obstructions.
- **Spoofing zone geography:** Field data maps a sustained spoofing zone near Port Sudan (~20.5°N) with a surrounding fringe zone (~21°14'N to ~22°03'N) where GPS intermittently toggles between real and spoofed positions. The intermittent pattern is consistent with a vessel at the edge of a ground-based spoofing transmitter's effective range, where real and spoofed GPS signals compete at similar power levels.
- **Spoofing detection confirmed:** SLGPS spoofing detection fired correctly in all scenarios. CSV telemetry from the Mini captured 14 alerts with warn_count reaching 14 during active spoofing (Section 11.12). During very rapid intermittent spoofing on SV JAMS, alerts fired correctly but reset between 60-second log entries; B&G navigation alarms confirmed the AIS Safety Related Text messages were sent (Section 11.11). A sliding-window detector is being added to improve detection of rapid intermittent patterns.
- **Operational accuracy:** Underway median deltas ranged from 14.9m (Standard Actuated at 3.6 kt) to 32.2m (Performance (Gen 2) at 5.9 kt). At-anchor accuracy reached 4.9m median on the Starlink Mini at Suakin (Section 11.12) — nearly 4x better than the underway floor. All results are consistent with the ~18m hardware floor established in the controlled tests.

11.1 Extended Passage — Rui Alheiro, SV Anne Charlotte (Starlink Mini, 13.2 Hours)

An overnight passage collected 789 valid samples over 13.2 hours at an average of 6.15 knots, using --poll 2, --history 3, --smoothing 45. This represents the longest continuous SLGPS logging run to date.

Metric	Value
Duration	13.2 hours (21:11Z Feb 20 – 10:25Z Feb 21)
Valid samples	789
Average SOG	6.15 kt
Median divergence	24.2m
Mean divergence	24.5m
Std deviation	7.1m
P90	34.2m
Max	47.3m
SOG agreement	0.473 kt
COG agreement	4.1°
Spoofing alerts	0
Samples > 50m	0 (0%)

Table 16: Rui Alheiro (SV Anne Charlotte) extended passage results. Starlink Mini dish, DataHub SLGPS.

Key finding: Performance is consistent over 13 hours — no degradation, no drift, zero spoofing alerts, zero samples above 50m. The 24.2m median matches the 1-hour controlled test (24.2m adjusted), confirming long-term stability.

Speed Range	Samples	Median	Mean	Range
3–5 kt	19	17.5m	18.7m	10–30m
5–7 kt	738	24.4m	24.6m	6–47m
7–9 kt	32	28.5m	26.6m	11–40m

Table 17: Divergence by vessel speed confirms expected physics — accuracy improves at lower speeds.

11.2 Extended Passage — Bruce Toal, SV Wild Orchid (Standard Actuated Dish, 10.8 Hours)

A second vessel logged 10.8 hours using a Starlink Standard Actuated dish (compared to Rui’s Mini). Same SLGPS settings: --poll 2, --history 3, --smoothing 45. The data reveals three distinct phases: good operation, a Starlink disconnect, and recovery.

Phase	Duration	Samples	Description
Good operation	7.0 hours (22:01–04:53Z)	409	Normal tracking. 27.4m median at 6.69 kt avg.
Starlink disconnect	94 minutes (04:54–06:28Z)	94	Dish lost satellite lock. Position froze. Deltas grew to 22 km.
Recovery	2.2 hours (06:29–08:43Z)	134	Operator disabled exclusive mode. Normal tracking resumed: 31.5m median at 7.28 kt.

Table 18: Bruce Toal (SV Wild Orchid) passage phase breakdown. Standard Actuated dish, motor disabled, exclusive mode.

Good Period: Standard Actuated vs Mini

Metric	Rui (Mini, 13.2 hr)	Bruce (Std Actuated, 7.0 hr)	Difference
Avg SOG	6.15 kt	6.69 kt	+0.54 kt
Median divergence	24.2m	27.4m	+3.2m
Std deviation	7.1m	7.5m	+0.4m
P90	34.2m	36.6m	+2.4m
SOG agreement	0.473 kt	0.303 kt	Bruce better
COG agreement	4.1°	2.2°	Bruce better
Max divergence	47.3m	46.0m	Comparable

Table 19: Good-period comparison. The ~3m median difference is largely explained by Bruce’s higher speed.

Dish comparison: During normal operation, the Standard Actuated dish performs within ~3m of the Mini. The difference is largely explained by Bruce’s higher average speed (+0.54 kt ≈ +2–3m DR drift). Velocity agreement is actually better on the Standard Actuated. The data does not support a significant accuracy disadvantage for the Standard Actuated dish during stable tracking.

Starlink Disconnect Event

At 04:54 UTC, the Starlink dish lost satellite lock while the vessel was sailing at 7.5 knots. The dish (motor disabled) continued to report **status=OK** while returning frozen or wildly jumping positions:

- Starlink SOG dropped to 0.0 kt while GPS confirmed 7.5 kt vessel speed
- Position froze at a stale reference point, with delta growing linearly
- Periodic position jumps between two stale references (oscillation pattern)
- Occasional absurd SOG spikes (261 to 3,215 kt) from position jump artifacts
- Maximum divergence reached 22.3 km (12.0 NM) after 94 minutes
- No error flag from the dish — starlink_status remained “OK” throughout

The operator resolved the issue by disabling exclusive positioning mode, which allows the dish to use GPS for satellite acquisition. Starlink reconnected within minutes and resumed normal independent position reporting (post-recovery positions show 12–50m deltas, confirming Starlink is computing its own position, not passing through GPS).

11.3 Signal-K Comparison — SV Wild Orchid (Same Standard Actuated Dish)

A 24-minute test compared Signal-K (reading Starlink position directly via a community plugin) against the chartplotter GPS and DataHub SLGPS, all running simultaneously on the same vessel and dish. Signal-K samples at 15-second intervals with no averaging or smoothing applied to the Starlink position data.

Attribute	DataHub SLGPS	Signal-K Plugin
Position source	Starlink API	Starlink API (same)
Averaging	3-sample position history	None
Smoothing	45% EMA	None
Coordinate precision	6 decimal degrees (0.1m)	2 decimal minutes (18.5m)
Sample rate	Every 2–5s (configurable)	Every 15s
Navigation output	NMEA 0183 TCP server	Signal-K data stream

Table 20: Processing pipeline comparison between DataHub SLGPS and Signal-K plugin.

Results: Good Tracking Period (~5.5 minutes)

During normal operation at ~8 kt, Signal-K tracked GPS within 0–19m (the 18.5m coordinate resolution limit). All three sources (Starlink via Signal-K, chartplotter GPS, and DataHub SLGPS) agreed within one grid step. No smoothing artifacts were detected in the Signal-K data — position steps are purely quantized grid jumps with no EMA lag signature.

Results: Starlink Disconnect (~15 minutes)

The same freeze/jump pattern observed in Bruce's overnight DataHub log appeared in the Signal-K data. Starlink position froze at a stale reference point while the vessel continued sailing at 7.8 kt. The DataHub column in Paul's log shows the same frozen position, confirming both Signal-K and DataHub read identical data from the Starlink API — the problem is at the dish level, not in the reading software.

Maximum divergence reached 4,854m (2.62 NM) over the 15-minute disconnect. The test was terminated after 20 minutes due to the dish reporting loss of connection while in exclusive positioning mode.

Smoothing Impact on Navigation

The Signal-K plugin passes through raw, unprocessed Starlink positions with no averaging or smoothing. The SLGPS system applies 3-sample position history averaging and 45% EMA smoothing specifically to produce a stable, navigation-grade track. While the coordinate resolution of the Signal-K log prevents direct accuracy comparison below ~20m, the DH column in the same log reveals the smoothing effect: DataHub positions consistently lag the chartplotter by ~18m (one grid step), the characteristic signature of the EMA damping. Signal-K shows no such lag.

Practical difference: Raw Signal-K positions will produce a noisier helm display and less stable autopilot input than SLGPS smoothed output. For spoofing detection, raw positions react faster to divergence changes but also produce more false jitter. For navigation, the SLGPS smoothing provides a meaningfully better user experience.

Key Conclusions from Cross-Platform Testing

- **Both platforms read the same Starlink data:** During the disconnect, Signal-K and DataHub show identical frozen positions. The freeze is a dish-level issue.
- **Standard Actuated dish accuracy matches Mini during normal operation:** The ~3m median difference is speed-dependent, not dish-dependent.
- **Exclusive-mode stalling is a platform-wide concern:** All non-Mini dishes tested — Standard Actuated (Bruce, Jörg, Paul Bouchier), Performance (Gen 2) (Jason Ball), and Performance (Gen 2) (Sandra Dethier, John Currell) — exhibit position stalling in exclusive mode. Rui's Mini logged 13.2 hours in exclusive mode without interruption. The non-Mini dishes also lose internet connectivity during stall events.
- **Spoofing zone behavior depends on dish type:** In exclusive mode, all non-Mini dishes stall on moving vessels due to the beam-steering circular dependency. In GPS spoofing zones with exclusive mode OFF, both mobile dishes (Mini and Performance (Gen 2)) provide reliable K-Band navigation. The Performance (Gen 2) navigated through sustained spoofing

near Port Sudan, confirmed by tracking website data (Section 11.7). The Standard Actuated shows intensity-dependent behavior: live K-Band at anchor during sustained spoofing (Section 11.10) and underway during intermittent spoofing (Section 11.11), but fails underway during sustained spoofing with phantom obstructions (Section 11.9).

- **Signal-K coordinate resolution is insufficient for accuracy analysis:** At 0.01 minutes (18.5m), deltas below ~20m are indistinguishable from zero. Higher precision logging is needed for meaningful comparison.

11.4 Extended Passage — Jörg Rosbach, SV JAMS (Standard Actuated Dish, 12.4 Hours)

A fourth vessel provided 12.4 hours of continuous SLGPS data using a Starlink Standard Actuated dish in the Gulf of Aden (~14°N, 50°E). Configuration: --poll 3, --history 3, --smoothing 60. The dish was operating in non-exclusive mode (GPS-assisted positioning) with the motor disabled, mounted inside the vessel under a hatch. Sea conditions were very calm with little wind and almost no swell. Note: the operator later discovered exclusive mode was not enabled for this session; subsequent sessions with exclusive mode enabled produced position stalls (see below).

Metric	Value
Duration	12.4 hours (00:00Z – 12:24Z Feb 27)
Valid samples	736
Average SOG	5.32 kt
Median divergence	21.7m
Mean divergence	23.3m
Std deviation	9.1m
P90	36.0m
Max	57.7m
SOG agreement	0.234 kt
COG agreement	1.6°
Stall events	0
SL SOG anomalies	0
Samples > 100m	0 (0%)

Table 21: Jörg Rosbach (SV JAMS) extended passage results. Standard Actuated dish, non-exclusive mode, inside mount, motor disabled.

Key finding: With GPS-assisted positioning (non-exclusive mode), the Standard Actuated dish produced 12.4 hours of stall-free operation with the best velocity agreement of any vessel (0.234 kt SOG / 1.6° COG). However, subsequent sessions with exclusive mode enabled produced the same position stalling seen on other non-Mini units. The higher smoothing factor (60% vs 45%) contributes to tighter velocity tracking.

Speed Range	Samples	Median	P90	Range
< 3 kt	18	12.7m	17.5m	6.8–17.8m
3–5 kt	322	17.1m	23.9m	5.7–33.2m
5–7 kt	297	26.6m	35.5m	12.2–41.5m
> 7 kt	99	35.6m	47.2m	15.4–57.7m

Table 22: Divergence by vessel speed. Accuracy tracks inversely with speed, consistent with other vessels.

Standard Actuated Platform Validation

Jörg's data reveals an important pattern. With non-exclusive mode (GPS-assisted), the Standard Actuated dish operated cleanly for 12.4+ hours. In subsequent sessions with exclusive mode enabled, the same dish exhibited position stalling identical to Bruce Toal's Standard Actuated. Sandra Dethier on SV Bliss III with a Performance (Gen 2) dish confirms the same pattern: stalls with exclusive mode ON, clean operation with exclusive mode OFF. This confirms that position stalling in exclusive mode affects all non-Mini dish types, including the purpose-built marine Performance (Gen 2). Only the Starlink Mini has operated stall-free in exclusive mode.

Metric	Jörg (Std Actuated, non-excl.)	Bruce (Std Actuated, good per Red)	(Mini)
Duration	12.4 hours	7.0 hours	13.2 hours
Median delta	21.7m	27.4m	24.2m
P90 delta	36.0m	36.6m	34.2m
SOG agreement	0.234 kt	0.303 kt	0.473 kt
COG agreement	1.6°	2.2°	4.1°
Stall events	0 (12.4 hr)	1 (94 min)	0 (13.2 hr)
SL SOG anomalies	0	12 (up to 3,215 kt)	0
Smoothing	60%	45%	45%
Installation	Inside, under hatch motor disabled	Outdoor motor disabled	Standard mount
Exclusive mode	OFF	ON → OFF	ON

Table 23: Cross-vessel comparison. Non-Mini dishes operate stall-free in non-exclusive mode but stall in exclusive mode.

Non-exclusive mode eliminates stalls: Jörg's dish operated stall-free for 60+ hours in non-exclusive mode, then stalled within hours of switching to exclusive mode. Sandra Dethier's Performance (Gen 2) confirms the same pattern: stalls with exclusive ON, instant recovery with exclusive OFF. The dish also loses internet connectivity during stall events, confirming a complete loss of satellite lock — not just a positioning subsystem failure. In exclusive mode, the dish must use its own derived position for beam steering, creating a circular dependency that breaks when vessel motion causes momentary lock loss. With GPS-assisted mode, the dish always has a current position for beam steering and can reacquire satellites seamlessly.

11.5 Extended Passage — Sandra Dethier, SV Bliss III (Performance (Gen 2), 12.7 Hours)

A fifth vessel provided 12.7 hours of SLGPS data using a Starlink Performance (Gen 2) dish in the Indian Ocean (~8°N, 68°E). Configuration: --poll 2, --history 3, --smoothing 45. The dish was running in exclusive positioning mode and was already in a stall state when logging began. The operator switched to non-exclusive mode, the dish recovered immediately, and then operated cleanly for 10.2 hours. With exclusive mode re-enabled, Sandra reports the stalls return — consistent with all other non-Mini field data.

Phase	Duration	Samples	Description
Stall (exclusive ON)	86+ minutes (19:41–21:07Z)	86	Exclusive mode ON, already stalling at log start. 19.1 km max delta, 2,551 kt SOG spikes. Dominant cached position at 7.89°N 68.97°E.
Clean operation (exclusive OFF)	10.2 hours (21:08–08:20Z)	665	Switched to non-exclusive mode. 26.5m median at 5.81 kt avg. 3 isolated single-sample glitches (110–222m).

Table 24: Sandra Dethier (SV Bliss III) passage phase breakdown. Performance (Gen 2) dish.

Metric	Value
Duration (clean period)	10.2 hours (21:08Z Feb 27 – 08:20Z Feb 28)
Valid clean samples	665
Average SOG	5.81 kt
Median divergence	26.5m
Mean divergence	27.3m
Std deviation	9.0m
P90	38.9m
Max	76.1m
SOG agreement	0.172 kt
COG agreement	1.9°
Stall events (clean period)	0 sustained (3 single-sample glitches)

Table 25: Sandra Dethier (SV Bliss III) clean-period results. Performance (Gen 2), DataHub SLGPS.

Speed Range	Samples	Median	P90
3–5 kt	107	21.3m	31.7m
5–7 kt	524	27.2m	38.9m
> 7 kt	34	32.0m	45.6m

Table 26: Divergence by vessel speed. Accuracy tracks inversely with speed, consistent with other vessels.

Key finding: Sandra's data confirms that the Performance (Gen 2) exhibits the same exclusive mode stalling as the Standard Actuated. With exclusive mode ON, the dish stalled immediately; switching to non-exclusive mode produced instant recovery and 10.2 hours of clean operation (26.5m median, 0.172 kt SOG agreement — the second-best velocity agreement of any vessel). With exclusive mode re-enabled, stalls return. This confirms the beam-steering circular dependency affects all non-Mini dish types, including the purpose-built marine Performance (Gen 2). Notably, no SPOOFING_ALERT flags were generated during the stall — only SL_POSITION_STALL. The rapid cycling between cached and real positions may keep sustained divergence below the spoofing threshold, demonstrating why both detection layers (stall + spoofing) are necessary.

Single-sample glitches: Three isolated events (204m, 110m, 222m) occurred during the 10-hour clean period, each recovering to normal accuracy in the next sample. These are a milder manifestation of the same position caching behavior — the dish returns a stale position for one poll cycle before reacquiring. They do not trigger spoofing or stall alerts and do not affect navigation.

11.6 Extended Passage — Jason Ball, SV Adventure (Performance (Gen 2), 56 Hours)

A sixth vessel provided 56 hours of continuous SLGPS data using a Starlink Performance (Gen 2) dish in the Indian Ocean (~6.3°N 74.9°E to ~7.1°N 72.9°E, then at anchor). Configuration: --poll 3, --history 4, --smoothing 60. Exclusive positioning mode OFF. The dataset includes 21.5 hours underway followed by 43 hours at anchor, producing the longest and cleanest non-Mini dataset collected to date.

Metric	Underway (21.5 hr)	At Anchor (43 hr)
Samples	1,253	~2,468
Avg SOG	5.90 kt	< 1 kt
Median delta	32.2m	10.2–11.7m
P90 delta	44.2m	15.1–15.7m
Max delta	181.5m (single spike)	24.0m
Std deviation	11.4m	3.4–4.4m
SOG agreement	0.158 kt	N/A (stationary)
COG agreement	2.0°	N/A (stationary)
Stall events	0	0
SL SOG anomalies	0	0

Table 27: Jason Ball (SV Adventure) results. Performance (Gen 2), exclusive mode OFF.

Speed Range	Samples	Median	P90
1–3 kt	10	7.2m	20.7m
3–5 kt	92	24.6m	34.6m
5–7 kt	1,104	32.8m	44.1m
> 7 kt	47	39.5m	53.0m

Table 28: Divergence by vessel speed (underway period only).

Key finding: Jason’s data is the longest stall-free non-Mini underway session collected (21.5 hours) and confirms the Performance (Gen 2) operates reliably with exclusive mode OFF. His SOG agreement of 0.158 kt is the best of any vessel tested. The slightly higher median delta (32.2m vs 21–27m on other vessels) is consistent with his --poll 3 setting, which allows more dead-reckoning drift between fixes. The stationary baseline of 10–12m across 43 hours at anchor is the tightest we’ve measured, confirming the Performance (Gen 2)’s excellent K-Band ranging precision.

Isolated high-delta samples: Four samples exceeded 100m during the 21.5-hour underway period (181m, 178m, 100m, 109m). None are stall events — SL SOG tracked GPS SOG correctly in all cases. The 181m sample had a fix age of 62 seconds (vs normal 7–12s), indicating a brief API response delay. All recovered to normal in the next sample.

11.7 Red Sea Transit — John Currell, SV Bojangles (Performance (Gen 2))

SV Bojangles provided SLGPS data using a Starlink Performance (Gen 2) dish in the Red Sea. Configuration: --poll 2, --history 3, --smoothing 45, exclusive mode OFF. The dish produced 77 minutes of clean data off the Eritrean coast (~15–16°N, 41°E) at an average speed of 6.64 kt.

Metric	Value
Duration	77 minutes
Samples	77
Avg GPS SOG	6.64 kt
Median delta	31.4m
P90 delta	39.2m
Max delta	45.2m
SOG agreement	0.219 kt
COG agreement	1.9°
Stalls	0

Table 29: John Currell (SV Bojangles) Performance (Gen 2), exclusive OFF.

Speed Range	Samples	Median	P90
5–7 kt	72	31.4m	39.2m
> 7 kt	4	37.0m	N/A

Table 30: Divergence by vessel speed.

Key finding: The Performance (Gen 2) — Starlink’s purpose-built marine dish — delivered 31.4m median accuracy at 6.64 kt with 0.219 kt SOG agreement and 1.9° COG agreement. These results are consistent with the other field tests and the controlled validation data, confirming the Performance (Gen 2) operates correctly with SLGPS in non-exclusive mode.

GPS Spoofing Zone Transit (Mar 11–13, Port Sudan to Northern Red Sea)

SV Bojangles subsequently transited through the active GPS spoofing zone near Port Sudan and northward through the Red Sea. During the transit, all vessel GPS systems were affected by spoofing — no GPS receiver on board was providing valid positions. The Performance (Gen 2) operated with exclusive mode OFF and DataHub SLGPS as the sole navigation source.

The Performance (Gen 2) provided **continuous, live K-Band position updates throughout the spoofing zone**. The vessel’s PredictWind tracking website confirmed an unbroken track with no gaps, no position jumps, and no frozen positions during the entire transit. The crew used the Starlink-derived position as their primary navigation source, cross-checking against the tracking website every 15 minutes and plotting positions on paper charts.

Key finding: The Performance (Gen 2) is **confirmed reliable through active GPS spoofing** in non-exclusive mode. The dish provided continuous K-Band navigation through the same sustained spoofing zone near Port Sudan where Standard Actuated dishes experienced phantom obstructions and connectivity loss (Section 11.9). This confirms that both purpose-built mobile Starlink dishes — the Mini and the Performance (Gen 2) — can maintain independent K-Band positioning regardless of GPS spoofing conditions. The Performance (Gen 2) joins the Mini as a recommended dish for GPS-threatened waters.

11.8 Spoofing Zone Transit — Theodore (Starlink Mini, Red Sea)

A cruiser identified as Theodore reported operating a Starlink Mini while transiting the Red Sea from Djibouti through Eritrean, Sudanese, and Egyptian waters. This vessel did not use DataHub SLGPS, so no CSV telemetry is available, but the operational report provides the first confirmed field evidence of Starlink positioning under active GPS spoofing while underway.

Near Suakin, Sudan (approximately 30 nautical miles north and south of the port), the vessel's GPS/GNSS system began reporting unrealistic positions and speeds. Upon detecting the spoofing, the crew enabled "Use Starlink positioning exclusively" on the dish and switched their navigation source to Starlink. They manually cross-checked the Starlink position against known landmarks and chart references. The Starlink position remained consistent and logical throughout the spoofing event — Theodore reported never losing position with Starlink. The crew continued navigating on Starlink while monitoring the GPS position. After several hours, the GPS position gradually converged back to the Starlink position and stabilized. The crew then switched back to GPS as the primary source.

Key finding: This is the first confirmed report of a Starlink dish providing reliable navigation through an active GPS spoofing zone while underway. Notably, the crew enabled exclusive mode as a response to the spoofing event — the Mini successfully transitioned from GPS-assisted to exclusive beam steering mid-transit in an active spoofing zone without losing satellite lock or position. The Mini never lost position throughout the event. The crew performed exactly the manual version of what SLGPS automates: compare GPS against Starlink, detect the anomaly, and fall back to the trustworthy source. The multi-hour GPS recovery timeline is consistent with the vessel transiting out of the spoofing zone's effective radius.

Operational confirmation: Theodore's report confirms the Mini's viability as a spoofing-resistant navigation source in the Red Sea corridor — one of the most heavily GPS-spoofed maritime regions in the world.

11.9 Spoofing Zone Transit — Thomas Knudsen (Mini) & SV Kia Maru (Standard Actuated), Red Sea

Two vessels transited a GPS spoofing zone near Port Sudan in the Red Sea simultaneously during a 12-hour overnight passage. Thomas Knudsen operated a Starlink Mini; his buddy boat SV Kia Maru (Vincent and Sarah Stockdale) operated a Standard Actuated dish. Neither vessel used DataHub SLGPS, but their operational reports provide critical field evidence comparing Mini and Standard Actuated behavior under active GPS spoofing — and the results are definitive.

Thomas Knudsen — Starlink Mini

The Mini worked flawlessly in both exclusive and non-exclusive modes throughout the 12-hour spoofing event. Position precision was below 10 meters most of the time. On two occasions overnight, the Starlink app reported losing GPS connection, but with exclusive mode enabled the dish continued providing position. Thomas reported that the Mini appeared to automatically choose the best source when exclusive mode was toggled. This is the most extensive confirmed Mini operation in a spoofing zone — 12 continuous hours with sub-10m precision.

SV Kia Maru 2014 Standard Actuated Dish

The Standard Actuated dish failed in **both** exclusive and non-exclusive modes. The crew experienced multiple connectivity fallouts with internet going on and off. When they tried switching between modes, Starlink reported phantom obstacles that did not exist, preventing the dish from establishing or maintaining a satellite connection. The crew was unable to navigate through reefs that the Mini-equipped vessel passed safely.

The Starlink mobile app's obstruction map confirmed the phantom obstructions visually: a large obstruction zone appeared to the east of the dish, with the app warning "Starlink is partially obstructed" despite a completely clear sky. The obstruction pattern was not present before entering the spoofing zone and cleared after exiting it, confirming that the spoofed GPS data was corrupting the dish's obstruction detection system. The vessel's navigation display showed the spoofed GPS track as a line of boat icons running north-northeast from the vessel's true position, and the vessel's tracking website confirmed the same spoofed track. The Starlink app also displayed large position uncertainty values during the spoofing event.

This is a critical finding. The beam-steering analysis in Section 2 predicted that a Standard Actuated dish in non-exclusive mode should maintain satellite lock in a **spoofing** zone, because even a spoofed GPS position is close enough for beam geometry. **The field data contradicts this prediction.** The Standard Actuated could not maintain connectivity in either mode. The phantom obstacle reports suggest the spoofed GPS data is corrupting the dish's beam steering **and** obstruction detection in ways more severe than a simple position offset — the dish's firmware uses GPS data for obstruction mapping and beam planning, not just beam angle computation. The Performance (Gen 2), by contrast, has been confirmed reliable through the same spoofing zone (Section 11.7), indicating that the phantom obstruction vulnerability is specific to the Standard Actuated platform.

Critical finding: Standard Actuated dishes are **unreliable underway in sustained GPS spoofing zones**. SV Kia Maru's Standard Actuated failed in both modes during a 12-hour spoofing event near Port Sudan. The dish reported phantom obstacles, lost internet connectivity repeatedly, and could not provide reliable navigation. The crew described the situation as untenable for reef navigation. Both mobile Starlink dishes — the Mini on the buddy boat and the Performance (Gen 2) on SV Bojangles (Section 11.7) — navigated through the same spoofing zone without issue.

Operational notes: GPS spoofing in this area appears centered around Port Sudan and was observed only during dark hours. Thomas recommends staying well offshore with a Standard Actuated dish. The Standard Actuated on SV Kia Maru did obtain occasional fixes between connectivity losses, suggesting intermittent satellite lock during lulls in spoofing intensity.

11.10 Spoofing Zone at Anchor — Jörg Rosbach, SV JAMS (Standard Actuated, 24 Hours)

SV JAMS provided 24 hours of continuous SLGPS data while at anchor near Port Sudan on March 11, capturing both clean daytime operation and a GPS spoofing event that activated at night. This is the same spoofing zone where SV Kia Maru's Standard Actuated failed underway (Section 11.9). Configuration: --poll 2, --history 4, --smoothing 60. Exclusive mode OFF throughout.

Phase	Duration	Samples	Description
Clean (daytime)	05:45–21:34 Mar 11	940	GPS active, no spoofing. 9.5m median delta at anchor. Best Standard Actuated at-anchor accuracy.
GPS VOID (pre-spoof)	21:34–22:42	68	GPS signal lost. SL continues providing live K-Band fixes.
Spoofing (night)	22:42–23:59 Mar 11	78	GPS spoofed at 38.6 kt due east. GPS went VOID after 2 samples. SL K-Band: LIVE, FRESH fixes.
Post-spoof (underway)	03:46–06:43 Mar 12	176	Departed anchorage. GPS clean. 14.9m median at 3.6 kt. No stalls.

Table 31: Jörg Rosbach (SV JAMS) 24-hour session including GPS spoofing event. Standard Actuated, exclusive OFF.

Metric	Clean (daytime)	During Spoofing
Samples	940	78
SL fix age (median)	5.9s	4.4s
SL fix age (max)	—	8.3s
Unique SL positions	(updating)	70 (updating)
SL SOG	Normal	0.000 (at anchor)
SL stalls	0	0
Median delta	9.5m	N/A (GPS VOID)

Table 32: Standard Actuated K-Band performance: clean vs spoofing period (at anchor).

Key finding: The Standard Actuated dish continued providing **live, fresh K-Band positions throughout the GPS spoofing event** while at anchor. Fix ages during spoofing (median 4.4s, all under 10s) were actually better than during the clean daytime period (median 5.9s). The K-Band position showed 70 unique coordinates across 78 samples — normal anchor drift, not a frozen cache. The dish was completely unaffected by the spoofing.

Standard Actuated at-anchor resilience: The Standard Actuated's ability to provide live K-Band fixes at anchor during sustained spoofing is significant for vessels waiting to transit through spoofed waters. Combined with the Standard Actuated's confirmed performance underway during intermittent spoofing (Section 11.11), this demonstrates partial spoofing resilience. The limitation is sustained spoofing underway, where phantom obstructions disrupt beam steering (Section 11.9). Both mobile dishes (Mini and Performance (Gen 2)) have been confirmed reliable through sustained spoofing in all conditions.

11.11 Underway Spoofing Transit — Jörg Rosbach, SV JAMS (Standard Actuated, Mar 12–13)

SV JAMS provided 24 hours of data while underway from Port Sudan northward on March 12, during which GPS spoofing was active for approximately 5 hours (18:00–23:00 UTC, from ~21°16'N to past 22°03'N). This is the first instrumented Standard Actuated underway transit through a GPS spoofing zone with SLGPS telemetry. Configuration: --poll 2, --history 4, --smoothing 60. Exclusive mode OFF. The spoofing was confirmed by Jörg's observation that all iOS devices were affected and B&G navigation displayed spoofing alarms.

Intermittent Spoofing Pattern

Unlike the sustained spoofing at Port Sudan (where GPS stayed spoofed continuously), this spoofing was **intermittent** — GPS rapidly alternated between spoofed and correct positions:

Metric	Value
Spoofing window	18:00–23:00 UTC (~5 hours)
Total samples in window	356
Spoofed samples (delta > 50 km)	54 (15%)
Clean samples (delta < 200m)	302 (85%)
Spoofed GPS position	~19.38°N, 37–42°E (210–580 km east)
Spoofed GPS SOG	38–46 kt heading east
Spoofed burst count	43 separate bursts
Burst lengths	34x single, 6x two, 3x three samples
Max consecutive spoofed	3 samples

Table 33: Intermittent GPS spoofing pattern during underway transit.

Standard Actuated K-Band: Flawless Underway During Spoofing

The Starlink K-Band position was live, accurate, and completely unaffected throughout the 5-hour spoofing window:

Metric	Value
Samples in spoofing window	356
Unique SL positions	356 (every sample different)
SL SOG > 0	356 of 356 (tracking vessel motion)
SL SOG median	4.98 kt
SL fix age	median 6.8s, max 10.6s (all fresh)
SL position stalls	0
SL track distance	50 km north (tracking passage)
Delta (clean GPS samples)	median 18.2m, P90 26.8m

Table 34: Standard Actuated K-Band performance underway during intermittent spoofing.

Key finding: The Standard Actuated dish provided **flawless K-Band navigation underway during 5 hours of intermittent GPS spoofing**. Every sample had a unique position, SL SOG tracked vessel motion, fix ages were fresh (median 6.8s), and accuracy on clean-GPS samples was 18.2m median — identical to normal operation. The dish tracked 50 km of northward passage while GPS was intermittently reporting the vessel 210–580 km to the east. This demonstrates that the Standard Actuated can tolerate intermittent spoofing underway because the spoofed GPS does not persist long enough to corrupt beam steering — the dish recovers during the clean intervals between spoofed bursts.

CSV Logging of Very Short Spoofing Bursts

Despite 54 spoofed GPS samples visible in the CSV over 5 hours with deltas of 210–580 km, the CSV log shows `spoofing_alert_active=0` on every entry and `max_gps_warn_count=4`. However, Jörg reported multiple spoofing alarms on his B&G Triton display during the night. These alarms were triggered by AIS Safety Related Text messages sent by SLGPS when the spoofing alert fires. This confirms the detection algorithm **did** work — the alert fired and was transmitted to the navigation system — but Jörg’s very short burst pattern (1–3 samples) caused the alert to fire and reset between 60-second log entries.

The mechanism: with `--poll 2` (effective ~2.7s on DataHub), approximately 22 polls occur between each 60-second log entry. During a spoofed burst, the `warn_count` climbs past the threshold of 5, fires the alert, sends the AIS SAR message, then resets when GPS returns to the correct position — all between log entries. The CSV captures only the instantaneous state at the moment of logging, which by then shows `warn_count` back near zero.

gps_warn_count (at log time)	Occurrences	Note
0	1,365	Counter reset after alert fired and cleared
1	42	Counter rising on new spoofed burst
2	10	Counter rising
3	5	Counter rising
4	3	Highest captured — exceeded 5 between entries

Table 35: Warn count as captured in 60-second CSV log. The counter exceeded the threshold of 5 between log entries but had reset by the time of capture.

Detection confirmed: SLGPS spoofing detection worked correctly for this intermittent spoofing pattern. The B&G Triton alarms prove the AIS Safety Related Text messages were sent, which only happens when the `warn_count` exceeds the threshold. The CSV logging gap is specific to Jörg’s very short burst pattern (1–3 samples), not a systemic issue — SV Anne Charlotte’s spoofing data (Section 11.12) showed `warn_count` reaching 14 and 14 `SPOOFING_ALERT` entries correctly captured at the same 60-second log interval. A sliding-window spoofing detector has been added to the SLGPS software to improve detection of rapid intermittent patterns like Jörg’s.

Spoofing intensity matters for Standard Actuated: SV Kia Maru’s Standard Actuated failed underway near Port Sudan (Section 11.9) where spoofing was sustained and intense. Jörg’s Standard Actuated worked perfectly underway through intermittent spoofing 15 nm offshore. The critical factor for Standard Actuated dish failure is whether the spoofed GPS persists long enough to corrupt beam steering. Both mobile dishes (Mini and Performance (Gen 2)) operated through sustained spoofing without issue (Sections 11.7–11.8). Mar 13 data showed fully clean operation past 22°03’N (308 samples, 20.5m median, zero spoofing alerts).

11.12 Spoofing Zone Transits — Rui Alheiro, SV Anne Charlotte (Starlink Mini, Mar 19 & 21)

SV Anne Charlotte provided the first SLGPS CSV telemetry from a Starlink Mini operating through active GPS spoofing. Two separate spoofing events were captured near Suakin, Sudan — one intermittent and one sustained — providing a direct comparison of how spoofing intensity affects Mini positioning accuracy.

Rui reports that during both events, iPhones lost their positions first, followed by all other GPS equipment on board (MFD, AIS, DataHub built-in GPS). Android phones on both SV Anne Charlotte and the buddy boat resisted the intermittent spoofing (Mar 19) but were also affected during the sustained spoofing event (Mar 21).

Event 1: Intermittent Spoofing (Mar 19, Massawa → Suakin)

During the overnight approach to Suakin, SV Anne Charlotte encountered approximately 54 minutes of intermittent GPS spoofing between 05:25 and 06:19 UTC. Configuration: --poll 2, --history 3, --smoothing 50. Exclusive mode OFF.

Phase	Duration	Samples	Description
Underway (pre-spoofing)	00:00–05:24 Mar 19	323	Normal operation. 25.2m median, 5.2 kt avg. Zero alerts.
GPS spoofing active	05:25–06:18 Mar 19	53	GPS toggling between real (54%), spoofed to Saudi Arabia (17%), and no fix (30%). 14 alerts fired.
Post-spoofing approach	06:20–07:00 Mar 19	40	GPS recovered. 27.7m median. Approaching Suakin anchorage.
At anchor Suakin	07:00–09:06 Mar 19	124	4.9m median at anchor. Best at-anchor accuracy recorded from any Starlink dish.

Table 36: Event 1 — Massawa–Suakin passage with intermittent GPS spoofing. Starlink Mini, exclusive OFF.

Metric	Pre-Spoofing (underway)	During Spoofing (GPS-real only)	At Anchor (Suakin)
Samples	321 clean	29 (GPS real)	123 clean
Median delta	25.2m	27.8m	4.9m
P90 delta	37.9m	38.7m	9.7m
Max delta	86.5m	42.6m	26.0m
Avg SOG	5.2 kt	5.7 kt	0.2 kt
SL stalls	0	0	0
Spoofing alerts	0	14 of 53	0

Table 37: Event 1 — Mini K-Band accuracy before, during, and after intermittent spoofing. Accuracy unchanged.

Key finding (intermittent): The Mini’s K-Band accuracy was **unchanged during intermittent GPS spoofing**: 27.8m median during spoofing vs 25.2m before spoofing. Zero stalls, zero position anomalies, steady 5.7 kt SOG throughout. The GPS receiver alternated between real position (54%), spoofed to Saudi Arabia at 26°N (17%), and no fix (30%). SLGPS spoofing detection fired correctly on 14 of 53 samples.

At-anchor precision: The 4.9m median at Suakin is the best accuracy recorded from any Starlink dish in this study — nearly 4x better than the ~18m underway floor.

Event 2: Sustained Spoofing (Mar 21, Leaving Suakin)

Two days later, SV Anne Charlotte departed Suakin and encountered approximately 3 hours of sustained GPS spoofing from 03:13 to 06:00 UTC, followed by intermittent spoofing until approximately 06:45 UTC. The GPS was locked on a spoofed position at ~17.5°N heading east at ~39 kt for the entire sustained period — 0% of GPS samples showed the real position. Configuration: --poll 2, --history 3, --smoothing 50. Exclusive mode OFF.

Phase	Duration	Samples	Description
At anchor (spoofing start)	03:12–03:25 Mar 21	14	SL stationary (correct). GPS spoofed at 39 kt. 12 SL_POSITION_STALL false positives (see note below).
Sustained spoofing UW	03:25–06:00 Mar 21	155	GPS 100% spoofed. SL providing positions but SOG noisy: 73% normal, 17% >9 kt, 10% <3 kt.
Intermittent spoofing	06:00–06:45 Mar 21	45	GPS toggling. Delta measurable: 54.4m median (degraded).
Clean operation	06:45–12:29 Mar 21	339	GPS recovered. Normal accuracy. 23.0m median (06:45–11:00).

Table 38: Event 2 — Departure from Suakin with sustained GPS spoofing. Starlink Mini, exclusive OFF.

Metric	Intermittent (Mar 19)	Sustained (Mar 21)
Spoofing type	Intermittent (54% GPS real)	Sustained (0% GPS real, 3 hrs)
Duration	54 minutes	~3 hours
Exclusive mode	OFF	OFF
SL median delta (during spoofing)	27.8m (unchanged)	54.4m (degraded)
SL P90 delta	38.7m	94.3m
SL SOG noise	None (0%)	17% erratic (>9 kt)
SL stalls	0	0
Navigation viable?	Yes	Yes (degraded)
Recovery	Immediate	Immediate

Table 39: Comparison of Mini performance under intermittent vs sustained GPS spoofing. Both events non-exclusive mode.

Key finding (sustained): The Mini continued providing **usable navigation throughout 3 hours of sustained GPS spoofing**, but with degraded accuracy: ~54m median vs the usual ~25m, and noisy SOG (17% of samples erratic). This is the first time the Mini's accuracy has been measurably affected by spoofing. The degradation correlates clearly with spoofing intensity and duration. Accuracy recovered immediately once spoofing cleared — returning to 23.0m by 06:45 UTC.

Open question — exclusive mode: Both events were captured in non-exclusive mode, where GPS data is used by the dish for beam steering and potentially other firmware functions. Whether exclusive mode — which excludes GPS from dish operations entirely — would prevent the accuracy degradation during sustained spoofing is unknown. Field data from a Mini in exclusive mode during sustained spoofing is needed to answer this question.

Stall detection false positive: 12 SL_POSITION_STALL flags fired at anchor (03:13–03:25) because the stall detector used spoofed GPS SOG (39 kt) to confirm vessel motion, while the vessel was actually stationary. This is a bug: when SPOOFING_ALERT is already active, the stall detector should not trust GPS SOG for the motion cross-check.

11.13 GPS Spoofing Zone Analysis — Sustained vs Fringe Zones

The combined field data from seven separate GPS spoofing events near Port Sudan reveals a geographic structure to the spoofing that has practical implications for vessel routing and SLGPS behavior. The data maps two distinct zones around the spoofing source.

Sustained Spoofing Zone (~20.5°N, Port Sudan)

At or near Port Sudan, GPS spoofing is sustained and continuous. The spoofed GPS signal overwhelms the real GPS signal, and receivers lock onto the fake position for hours without interruption. This is where SV Kia Maru's Standard Actuated lost connectivity underway (Section 11.9) and Jörg's Standard Actuated provided live K-Band at anchor but would not have worked underway (Section 11.10). Both mobile dishes navigated through this zone successfully: the Mini (Sections 11.8–11.9) and the Performance (Gen 2) on SV Bojangles (Section 11.7). All iOS devices in the area were affected. Spoofing was most intense during dark hours.

Fringe Spoofing Zone (~21°14'N to ~22°03'N, 15 nm offshore)

Further from the spoofing source, the fake and real GPS signals are similar in strength. The GPS receiver's correlator flips between whichever signal is momentarily stronger, affected by vessel orientation, antenna gain pattern, wave motion, and atmospheric conditions. The result is rapid, random toggling between real and spoofed fixes — what Jörg's underway data captured (Section 11.11): 43 separate bursts of 1–3 spoofed samples across 5 hours, with 85% of samples showing the correct GPS position.

Several observations confirm this is a fringe effect rather than intentional intermittent spoofing: the burst pattern is random (not periodic), the spoofed position is always the same single vector (~19.38°N, ~39 kt east), Jörg sailed through the zone and out the other side (clean past 22°03'N), and sustained spoofing at the source (~20.5°N) produced continuous, uninterrupted GPS lock on the fake position.

Zone	Location	GPS Behavior	Std Actuated K-Band	Performance (Gen 2)
Sustained spoofing	~20.5°N (Port Sudan)	Locked on spoofed position continuously. All devices affected.	Anchor: OK (live). Underway: FAILS (phantom obstructions).	CONFIRMED reliable. (SV Bojangles tracking data).
Fringe spoofing	21°14'N – 22°03'N (15 nm offshore)	Toggles between real and spoofed. 15% of samples affected.	Fully operational. 18.2m median. Zero stalls.	Expected operational.
Clear	North of ~22°03'N	Normal GPS. No spoofing detected.	Fully operational. 20.5m median.	Confirmed operational.

Table 40: GPS spoofing zone geography and dish behavior by zone. Mini operates normally in all zones.

Operational implication: Intermittent GPS spoofing is a leading indicator that a vessel is approaching a sustained spoofing zone. If the SLGPS sliding-window detector fires while underway (GPS toggling between real and spoofed positions), the crew should be aware that sustained spoofing — which may disable Standard Actuated K-Band positioning on a moving vessel — lies closer to the transmitter source. Vessels with non-Mini dishes should increase visual navigation vigilance and consider routing further offshore where the fringe zone produces only intermittent interference that the Standard Actuated dish can tolerate.

Spoofing Zone Performance Comparison

The following table summarizes SLGPS performance across all vessels that operated in GPS spoofing zones, organized by dish type and spoofing intensity. This includes both DataHub CSV telemetry and operational reports without telemetry.

Vessel	Dish	Exclusive Mode	Spoofing Type	Duration	SL Median Delta	SL Stalls	Data Source
Rui (Anne Charlotte)	Mini	OFF	Intermittent	54 min	27.8m (unchanged)	0	CSV
Rui (Anne Charlotte)	Mini	OFF	Sustained (3 hrs)	~3 hrs	~54m (degraded)	0	CSV
Thomas Knudsen	Mini	ON	Sustained (12 hrs)	12 hrs	~10m (reported)	0	Operational report
Theodore	Mini	ON	Sustained	Multi-day	Sub-10m (reported)	0	Operational report
John Currell (Bojangles)	Perf (Gen 2)	OFF	Sustained	Transit	N/A	0	Tracking website
Jörg Rosbach (JAMS)	Gen 2 Std	OFF	Sustained (at anchor)	24 hrs	9.5m (clean period)	0	CSV
Jörg Rosbach (JAMS)	Gen 2 Std	OFF	Intermittent (underway)	5 hrs	18.2m	0	CSV
Kia Maru	Gen 2 Std	OFF	Sustained (underway)	12 hrs	FAILED	N/A	Operational report

Table 41: Spoofing zone performance comparison across all vessels. Mini operates in all conditions; Performance (Gen 2) confirmed through sustained spoofing; Gen 2 fails underway during sustained spoofing.

Key observations: (1) The Mini provides usable navigation in all spoofing conditions, though accuracy degrades during sustained spoofing in non-exclusive mode (~54m vs ~25m). Thomas Knudsen's 12-hour transit in exclusive mode with reported sub-10m accuracy suggests exclusive mode may prevent this degradation, but CSV telemetry is needed to confirm. (2) The Performance (Gen 2) navigated through sustained spoofing in non-exclusive mode (confirmed by tracking data). (3) The Gen 2 works at anchor during sustained spoofing and underway during intermittent spoofing, but fails underway during sustained spoofing. (4) Android phones resisted intermittent spoofing across multiple vessels but were affected during sustained spoofing — reason for the difference is unknown.

11.14 All Field Tests — Summary Comparison

	Rui	Bruce	Jörg	Sandra	Jason	John	Paul
Vessel	Anne Charlotte	Wild Orchid	JAMS	Bliss III	Adventure	Bojangles	Wild Orchid
Dish	Mini	Std Actuated	Std Actuated	Perf (Gen 2)	Perf (Gen 2)	Perf (Gen 2)	Std Actuated
Exclusive	ON	ON → OFF	OFF †	ON → OFF	OFF	OFF	ON
Duration	13.2 hr	10.8 hr (7.0 good)	12.4 hr	12.7 hr (10.2 good)	56 hr (21.5 UW)	77 min	24 min (5.5 good)
Avg SOG	6.15 kt	6.69 kt	5.32 kt	5.81 kt	5.90 kt	6.64 kt	7.8 kt
Median	24.2m	27.4m	21.7m	26.5m	32.2m	31.4m	< 18.5m *
P90	34.2m	36.6m	36.0m	38.9m	44.2m	39.2m	19m *
Stall?	None	Yes (94 min)	None	Yes (86+ min)	None	None	Yes (15 min)
Max stall delta	N/A	22.3 km	N/A	19.1 km	N/A	N/A	4.9 km

Table 42: Cross-platform field test summary. Paul used Signal-K (not DataHub SLGPS). (* Signal-K values limited by 18.5m coordinate resolution. † Jörg later enabled exclusive mode and experienced stalls.)

Acknowledgments

The conclusions and analysis in this report would not have been possible without the generous cooperation of the sailors and vessel owners who volunteered their time, their vessels, and their Starlink hardware as real-world test platforms. Each tester installed DataHub SLGPS, collected telemetry data under operational conditions, and provided detailed observations that shaped our understanding of Starlink positioning — particularly in the challenging GPS spoofing environment of the Red Sea.

Tester	Vessel	Dish Type	Contribution
Rui Alheiro	SV Anne Charlotte	Starlink Mini	Controlled validation passage (13.2 hr). First Mini CSV telemetry through GPS spoofing (Massawa–Suakin transit).
Bruce Toal	SV Wild Orchid	Standard Actuated	First non-Mini field test (10.8 hr). Exclusive mode stall discovery.
Paul Bouchier	SV Wild Orchid ‡	Standard Actuated	Signal-K comparison test. Alternative data path validation.
Jörg Rosbach	SV JAMS	Standard Actuated	Multiple sessions including 56+ hr total. Anchor + underway spoofing data. Fringe zone discovery.
Sandra Dethier	SV Bliss III	Performance (Gen 2)	Exclusive mode stall confirmation (12.7 hr). Clean non-exclusive data.
Jason Ball	SV Adventure	Performance (Gen 2)	Longest field test (56 hr). At-anchor accuracy baseline. Multi-day reliability.
John Currell	SV Bojangles	Performance (Gen 2)	Confirmed Perf (Gen 2) reliable through sustained GPS spoofing.
Theodore	—	Starlink Mini	First confirmed Mini transit through active GPS spoofing (Red Sea).
Thomas Knudsen	—	Starlink Mini	12-hour spoofing zone transit. Sub-10m precision confirmed. Kia Maru comparison.
Vincent & Sarah Stockdale	SV Kia Maru	Standard Actuated	Standard Actuated underway spoofing failure. Phantom obstruction screenshots. App diagnostics.

‡ Paul Bouchier performed the Signal-K analysis using data collected from Bruce Toal's SV Wild Orchid; he is not a crew member of that vessel.

These testers represent a community of cruising sailors who are actively navigating through some of the most GPS-threatened waters in the world. Their willingness to test experimental navigation technology on their own vessels — in some cases while transiting reefs at night in spoofed waters — reflects both the severity of the GPS spoofing problem and the potential of Starlink-based positioning as a solution. This report is dedicated to them.

Appendix A: Chartplotter & Navigation Software Setup

Once SLGPS is running on the DataHub and the Starlink dish is configured for position reporting (Section 1.3), the Starlink position data must be configured as a navigation source in the vessel's chartplotter or navigation software. The DataHub outputs SLGPS data via both NMEA 0183 (TCP network) and NMEA 2000 (backbone), so the connection method depends on the equipment.

A.1 NMEA 2000 Chartplotters (Raymarine, Garmin, B&G, Simrad, etc.)

Chartplotters connected to the vessel's NMEA 2000 backbone will automatically see the SLGPS position data as an additional GPS source. The Starlink-derived position appears as a separate device on the N2K bus. To use it:

- Navigate to the chartplotter's **GPS source** or **position source** settings.
- Select the SLGPS device (it will appear with the configured N2K device instance).
- On some chartplotters, you may need to enable **multiple GPS sources** or switch the primary source manually when GPS is compromised.

A.2 OpenCPN (via NMEA 0183 TCP)

OpenCPN can receive SLGPS data over a TCP network connection from the DataHub:

- Open OpenCPN and go to **Options** → **Connections**.
- Click **Add Connection** and select **Network / TCP**.
- Enter the DataHub's IP address and the SLGPS NMEA output port (default: 6000).
- Set the connection as a **Input** data source.
- OpenCPN will display the Starlink position as an available GPS source, identified by the "ST" talker ID in the NMEA sentences.

A.3 Navionics Boating App (via NMEA 0183 TCP)

The Navionics Boating app on iOS and Android can receive SLGPS position data over WiFi:

- Connect your phone/tablet to the DataHub's WiFi network.
- In Navionics, go to **Settings** → **External Sensors**.
- Enable **NMEA over WiFi** and enter the DataHub's IP address and SLGPS port.
- Navionics will use the Starlink position when the connection is active.

A.4 General NMEA 0183 Devices

Any device or software that accepts NMEA 0183 input via TCP can receive SLGPS data. Configure a TCP client connection to the DataHub's IP address on the SLGPS port. The sentences use the "ST" talker ID (GGA, RMC, VTG) and follow standard NMEA 0183 formatting with valid checksums.

Detailed setup guide: Step-by-step instructions with screenshots for specific chartplotters, OpenCPN, and Navionics are available online at: https://maddox-zephyr.github.io/starlink_position/pw_datahub_setup.html

END OF SLGPS VALIDATION REPORT

Data: 252 controlled test comparisons + 7 extended field tests + 5 spoofing zone reports | Confidence: HIGH